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Analysis of the business potential of product-service systems for investment goods

Joris Van Ostaeyen

Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Engineering

March 2014

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Voorwoord

"If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts he shall end in certainties." – Sir Francis Bacon

"Non menno che saper, dubbiar m'aggrata[1]." – Dante Alighieri

Toen ik eind 2008 terugkeerde uit India, het laatste land op onze wereldreisroute, kreeg ik de kans om het doctoraatsonderzoek aan te vatten dat resulteert in dit eindwerk. Mijn keuze om het bedrijfsleven in te ruilen voor de academische wereld, na ruim vier boeiende werkjaren bij Atlas Copco – eerst in Antwerpen, later in het Chinese Wuxi – verraste mijn omgeving. Ik kreeg dan ook ruimschoots gelegenheid om mijn beslissing te verantwoorden, op een moment dat ik zelf nog mijn weg aan het zoeken was op onbekend (onderzoeks)terrein. Pas vandaag, nu deze dissertatie voorligt, ben ik zeker dat mijn beredeneerde gok van toen een juiste was.

Bovenstaande citaten passen dus bij de persoonlijke weg die ik de afgelopen jaren heb afgelegd. Maar meer nog, geven ze perfect het inzicht weer dat centraal staat in dit werk: alleen door op een gepaste wijze rekening te houden met onzekerheden kunnen betekenisvolle besluiten getrokken worden over het zakelijk potentieel van product-dienstsystemen in een specifiek geval. Wie zekerheid wil, moet eerst de twijfel kennen om hem juist in rekening te kunnen brengen. Maar vooraleer ik overga tot de inhoud, wil ik enkele personen bedanken die een belangrijke rol gespeeld hebben bij de totstandkoming van dit werk.

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[1] Doubting charms me no less than knowledge.

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Alle vrienden en familie, jullie zal ik niet een voor een overlopen, maar dank voor de steun en de belangstelling. Wel nog een speciale vermelding voor mijn ouders, bedankt voor alle kansen die ik heb gekregen en jullie aanmoediging bij al mijn keuzes.

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Abstract

Over the last decade, insight has grown that between a pure product manufacturer and a pure service provider, various business model options exist, in which products and services are combined to varying degrees. This concept is described by the term Product–Service Systems (PSSs), which is the subject of a considerable amount of recent research attention. The overarching goal of the presented work is to analyze the business potential of a PSS from the point of view of a manufacturer of investment goods.

The PSS research field is often criticized for lacking maturity and a coherent terminology. In this thesis, a theoretical foundation for PSS research is proposed, including a new PSS definition, representation scheme and typology. Moreover, Functional Hierarchy Modeling is presented, a theoretical framework that allows to represent the functions of an investment good on different levels of abstraction. Three complementary approaches for PSS ideation, that support manufacturers in identifying a broad set of PSS options, are proposed and illustrated.

The second part of this dissertation presents a generic methodology to evaluate the business potential of a PSS. This methodology focuses on the innovation potential of a PSS in cost and value and allows to analyze the impact of risks and uncertainties. It is validated through its application on five in-depth case studies, performed for Belgian industrial manufacturers. The business potential of a PSS is analyzed for a manufacturer of elevators, a provider of lighting control systems, a provider of fire detection systems, a developer of diamond polishing systems and a manufacturer of wind turbine gearboxes.

Beknopte samenvatting

Het afgelopen decennium groeide het inzicht dat er tussen zuivere productverkoop en zuivere dienstverlening verscheidene businessmodellen bestaan, waarin producten en diensten op verschillende manieren worden gecombineerd. Dit concept, in de literatuur beschreven als product–dienstsystemen, is het onderwerp van heel wat recente onderzoeksinteresse. Deze dissertatie wil het zakelijk potentieel van een product-dienstsysteem (PDS) analyseren vanuit het standpunt van een fabrikant van investeringsgoederen.

Een regelmatig terugkerende kritiek is dat het PDS onderzoeksveld lijdt aan een gebrek aan maturiteit en een coherente terminologie. Deze dissertatie stelt een theoretische basis voor PDS onderzoek voor, die bestaat uit een definitie, een schematisch model en een typologie. Bovendien wordt Functionele Hiërarchie Modellering geïntroduceerd, een theoretisch raamwerk dat toelaat de functies van een investeringsgoed voor te stellen op verschillende abstractieniveaus. Verder worden drie complementaire benaderingen besproken voor het genereren van mogelijke PDS-opties. Er volgen industriële voorbeelden ter illustratie.

Het tweede deel van deze dissertatie presenteert een generieke methodologie om het zakelijk potentieel van een PDS model te evalueren. Deze methodologie spitst zich toe op het innovatiepotentieel van een PDS in kost en waarde en laat toe om de impact van risico's en onzekerheden te analyseren. Ze wordt gevalideerd door toepasing op vijf casestudies, uitgevoerd voor Belgische fabrikanten van investeringsgoederen. Het zakelijk potentieel van een PDS wordt onderzocht voor een fabrikant van liften, een aanbieder van lichtcontrolesystemen, een aanbieder van branddetectiesystemen, een ontwikkelaar van diamantslijpinstallaties en een fabrikant van tandwielkasten voor windturbines.

List of abbreviations

AB	Availability Based
ABC	Activity Based Costing
CMS	Condition Monitoring System
DPB	Discounted Payback Period
DPS	Diamond Polishing System
EAC	Equivalent Annual Cost
FDS	Fire Detection System
FHM	Functional Hierarchy Model(ing)
FMEA	Failure Modes and Effects Analysis
GIP	Grain Independent Polishing
IB	Input Based
ISC	In–Service Cost
LCC	Life Cycle Cost(ing)
LCS	Lighting Control System
LLB	Luminaires, Lamps, Ballasts
NPD	New Product Development
NPV	Net Present Value
NSD	New Service Development
PB	Performance Based
PB	Payback Period
PB-DO	Performance Based Demand Fulfillment Oriented
PB-EO	Performance Based Effect Oriented
PB-SO	Performance Based Solution Oriented
pdf	probability density function
PI	Profitability Index
PLC	Product Life Cycle
PSS	Product Service System
RPN	Risk Priority Number
TD-ABC	Time Driven Activity Based Costing
UB	Usage Based
WACC	Weighted Average Cost of Capital
WTP	Willingness To Pay

Contents

Chapter 1

Introduction

Confronted with ever fiercer global competition, many manufacturers of investment goods have identified the expansion of their service business as key to their future success [72, 154]. Various theoretical concepts have emerged in the scientific literature, in different streams of research, to describe this aspiration: the *'servitization of manufacturing'* [11], *'servicizing'* [171], *'functional sales'* [200], *'(Industrial) Product-Service Systems'* [76, 142] *'performance (based) contracting'* [88, 106], *'hybrid value creation'* [228], *'eco-efficient producer services'* [16] and the *'functional (service) economy'* [195, 196].

Among these approaches, the Product-Service System (PSS) concept in particular has gathered considerable research attention over the last decade. According to Baines et al. [10], a PSS is characterized by an *"integrated offering of products and services that delivers value in use"*. The PSS concept implies that between a pure product manufacturer and a pure service provider a spectrum of PSS options exists, in which products and services are combined to varying degrees. The more manufacturers move to the service side of this spectrum, the larger the share of services in their total revenue becomes. In case the offering is completely 'servitized', the manufacturer is no longer selling products but rather the functional results of these products.

Initially, around the turn of the millennium, the PSS approach was put forward by European environmental scientists as a promising avenue to achieve sustainable production and consumption patterns [76, 142]. According to this ecological rationale, if a manufacturer offers a PSS, he will assume more responsibilities over the lifetime of his products and will therefore be inclined to reduce their material and energy consumption. In that way, PSS could lead to a decoupling of economic succes from ecological impact [10, 142].

Some examples of a PSS are presented in Table 1.1.

Table 1.1: Examples of a Product–Service System.

Company	**Type of product**	**PSS description**
Xerox	office equipment	Leasing or pay-per-copy models [101]
Rolls-Royce	aircraft engines	Power-by-the-Hour service packages, whereby maintenance, repair and overhaul are charged at a fixed price per hour of flight to the customers (i.e. airline companies) [60]
Arcomet	construction cranes	Rental services, including assembly and disassembly
Atlas Copco	air compressors	Rental services or sales of compressed air per m^3
Michelin	truck tyres	Management of the complete tyre stock of a transportation company per kilometer driven [196]
Philips Lighting	lighting systems	Selling a promised level of illuminance in a building, according to a *Pay per Lux* concept [163]
Econation	smart light domes	Selling a light dome based on the amount of artificial lighting energy it can save [59]
Cockerill Maintenance & Ingénierie	shunting locomotives	Leasing of shunting locomotives for steel manufacturing
Hilti	professional construction tools	Fleet management service for customer's tools, whereby the availability of these tools is sold for a fixed monthly fee, including all repairs and replacements [69]

The ecological potential of a PSS can be illustrated with some of these examples. In its *pay-per-copy* model, Xerox retains owernship of its office equipment and thus has access to a repository of reusable components. This led to the development of an extensive remanufacturing program that saves raw materials and reduces waste [101]. In its Fleet Solution program, Michelin manages to increase the service life of tyres by re-grooving and re-treading them. Moreover, due to close monitoring of tyre pressure, the customer's fuel consumption can be reduced and the tyre service life extended [196].

Besides ecological advantages, a PSS can have important economic benefits as well. Many scholars emphasize the business potential of a PSS and see the implementation of this concept as a strategy to improve the competitiveness of manufacturers [10, 135]. For example, mainly through its Power-by-the-Hour model, Rolls-Royce managed to increase the service share in its revenues from 30% to 55% over a period of 15 years [60]. During the global crisis of 2008-2009, Hilti increased its sales by 26% and improved its operating profit (EBIT) to 12,1% thanks to its fleet management service [69]. Xerox reports that in

2012 approximately 84% of its revenue was annuity-based, including contracted services, maintenance, consumable supplies and financing, while only 16% come from the sales of new equipment [240].

The awareness of these potential economic benefits of a PSS model formed the main motivation for the presented research work. *The overarching goal of this dissertation is to analyze the business potential of a PSS from the point of view of a manufacturer of investment goods, who currently has a traditional, product-based business model, but who is interested in adopting a PSS.* What would a PSS mean for this company? Which PSS options are possible? What is the business potential of each option? What are the main factors that determine this business potential? These are the questions that this dissertation intends to answer. They are formalized in Section 1.2, after a brief state of the art of PSS research is presented in Section 1.1. The approach that was followed to tackle the research questions and the scope limitations are presented in Section 1.3. The main contributions of this dissertation are summarized in Section 1.4 and the content of its chapters is layed out in Section 1.5.

1.1 A brief state of the art of PSS research

The researcher who is given credit for putting PSS on the research agenda [144], although he did not use this term, is the Swiss environmental scientist Walter Stahel, who suggested the idea of a *"functional economy, that optimises the use (or function) of goods and services and thus the management of existing wealth. The economic objective of the functional economy is to create the highest possible use value for the longest possible time while consuming as few material resources and energy as possible"* [195]. In 1999, Goedkoop et al. coined the term *Product–Service System* for the first time in a report to the Dutch government [76]. Since then PSS research has expanded significantly. Figure 1.1 depicts the number of peer reviewed academic journal articles published between January 2000 and July 2013 with *Product-Service System(s)* in the title, abstract or keywords [1].

Despite the steady flow of new publications and an *"explosion of research projects"* [150] about Product–Service Systems in recent years, several authors have criticized the lack of maturity of this emerging research field:

- *"If PSS ever want to create a science field in its own right, it is paramount" [...] "to greatly enhance the scientific rigor in for instance case study research"* [213].

[1] All articles were identified by searching the scientific databases Emerald Insight, Elsevier ScienceDirect, Springer Link and Ingentaconnect. In total, after the articles thus found were manually selected and duplicates were removed, 185 articles were retained.

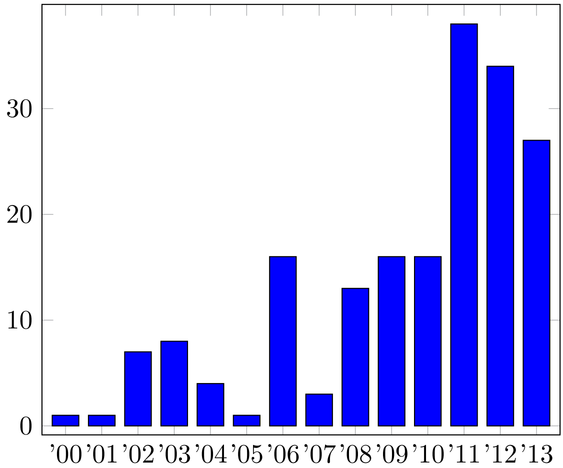

Figure 1.1: Number of academic journal articles with the term *Product–Service System(s)* in title, abstract or keywords, published between January 2000 and July 2013.

- *"In academia, many argue for a quantum jump in academic rigour in the design of tools/methodologies, with much better links to case studies to allow rigorous cross-case analyses* [10].*"*
- *"It seems that in this rush to design useful tools, the academic thoroughness and standard of the research was, to some extent, lowered* [145].*"*
- *"The field of PSS research is not fully mature* [225].*"*

A specific challenge for PSS researchers is the lack of a coherent terminology [26, 33, 132, 175]. There is an ample supply of definitions of PSS (e.g. [10, 26, 76, 126, 142, 150, 176, 212]) but none of them is widely accepted [26, 33]. The most often cited [22] definition states that a PSS is *"a marketable set of products and services capable of jointly fulfilling a user's need"* [76]. As Mont has noted [144], this definition implies that almost any manufacturer is already a PSS provider and therefore its usefulness seems limited. Other PSS definitions are more restrictive and demand for example that a PSS has a proven lowered environmental impact [142] or that in a PSS asset ownership should remain with the provider [175]. In certain definitions, PSS are characterized as a type of business model [211, 212], while in others they are described as a type of strategy [126] or as a type of offering [10]. To add to the confusion, the phenomenon described by PSS is studied independently under different terminologies in different streams of research, with only limited interconnections between them

[26, 176], as already indicated in the introductory paragraph of this chapter. As Plato argued in *Cratylus*, linguistic confusion arises when multiple terms refer to the same object or idea or when a single term refers to more than one object or idea [164]. Therefore, to avoid confusion, the first step should be to clarify the concept that the term PSS aims to describe. In our view, Monts statement made in 2004 that PSS research is in need of a coherent theoretical foundation [144], still holds in 2013. Specifically, clarification is required on what a PSS is, how it can be represented and which types of PSS can be discerned.

The PSS research field can be divided into subdisciplines that focus on particular aspects of this concept. By analyzing the 185 journal articles with the term Product–Service System(s) in abstract, title or keywords (cfr. Figure 1.1) in combination with the existing subdivisions of this research field [176, 228], the following subdisciplines can be discerned:

1. *PSS development and engineering* is concerned with PSS offer modelling, the PSS development process and the analysis of the PSS potential (both economic and environmental) [33, 176]
2. *PSS marketing* is mainly concerned with topics such as pricing and customer satisfaction [228]
3. *Strategy, innovation and organizational PSS research* is concerned with topics such as competitive advantage, business models and organizational design/transition [11, 228].
4. *Policy research for PSS* considers both macroeconomic and sustainability aspects relevant for policy makers.

Over the last years, many review articles were published in academic journals, that provide an overview of the work in (some of) these subdisciplines and that make suggestions for future research [10, 11, 22, 26, 33, 135, 145, 213, 225, 233]. Related to the goal of the presented research work, the following remarks are specifically relevant:

- For PSS research, an interdisciplinary approach is warranted. In the words of Sakao et al.: *"The boundaries to other research communities are getting blurry and many aspects of other professionalisms must be taken into account"* [176].
- Vasantha et al. describe a need for *"a good schema for representing PSS concepts with appropriate notation that avoids misinterpretation"* [225].
- One particular challenge for future research that is brought forward by Baines et al. is: *How can the value-in-use delivered by PSSs be assessed?*

[10]. Likewise, Wang et al. state that *“enterprises need quantitative tools to evaluate [...] the economic benefits of PSS”* [233].

- Boehm et al. state in their extensive review of the PSS field that *“in many cases developed PSS engineering approaches are applied solely in one case. This hampers the validity of the proposed procedure considerably. Of course, a comprehensive evaluation is time-consuming and costly. But it is necessary for achieving more practically relevant results”* [26]. Likewise, Cavalieri et al. state in their review of the PSS development and engineering subdiscipline that *“the practical application of existing theories in industry is really occasional”* and that *“the majority of contributions are mainly paper-based with scattered applications in real industrial contexts”* [33].

Thus, the main conclusions from this section are that on the one hand the PSS field is still in need of a sound theoretical foundation, and therefore sufficient attention should be paid to theory building. Specifically, clarification should be provided on what a PSS is and how it can be described unambiguously. On the other hand, there is a need for systematic methods and techniques to evaluate the business potential of a PSS. The available literature should be thoroughly scanned for relevant insights and approaches. These should be combined with insights from other research disciplines. Finally, a clear link with industrial reality is warranted to ensure the practical relevance of new theories and methods.

1.2 Research questions

From the point of view of a product-based industrial manufacturer, the potential economic benefits of a PSS are to be analyzed. Therefore, first it is paramount to understand clearly what a PSS is and which PSS options are possible for that particular manufacturer. As will be argued in detail in Chapter 3, the currently available definitions and typologies of PSS have several shortcomings. As indicated in the previous section, the PSS research field is still in need of a theoretical basis. This necessity inspires the formulation of the following, first set of research questions:

RQ_1: How can a PSS be unambiguously defined *(PSS definition)* and how can it be represented? *(PSS representation)*

RQ_2: Which basic types of PSS can be discerned? *(PSS typology)*

RQ_3: How can a broad set of PSS options be derived in a systematic way for a particular manufacturer of investment goods? *(PSS ideation)*

Subsequently, the business potential of (some of) the options derived by answering RQ_3 are to be analyzed. Hereby, two complementary perspectives should be taken into account: the ability of a PSS to reduce cost and its ability to add value. Both mechanisms contribute to what several authors call the *innovation potential of a PSS* [135, 146, 211], i.e. the potential a PSS holds to drive down overall costs and/or to increase the value for the customer, through a better alignment of the interests of provider and customers [132]. As will be argued in Section 3.4, a variety of theories, methods and tools is available in the current state of the art of PSS research, but a comprehensive methodology to analyze the innovation potential of a PSS according to the two mentioned perspectives is missing. Therefore, the following research questions are justified:

RQ_4: How can the potential of a PSS to reduce cost for the provider be analyzed in a systematic way?

RQ_5: How can the potential of a PSS to increase value for the customer be analyzed in a systematic way?

This second set of questions confronts us with specific difficulties and challenges. Firstly, because PSSs often entail a long term perspective on cost and value, various uncertainties and risks should be taken into account. Energy and material prices, times to failure, customer locations, usage intensities; these are only a few of the many factors that in most cases cannot be treated as deterministic values, but for which the uncertainty and variability should be dealt with appropriately. Secondly, to ensure the practical relevance of the systematic analysis of the cost and value potential of a PSS, specific questions of the target group should be answered, such as: for which customer segments and subsegments is the potential of a PSS maximal? What are the key technical and operational factors that determine the potential of a PSS? What are the advantages and disadvantages of various PSS models? An approach that intends to answer RQ_4 and RQ_5 should transcend the purely theoretical level and should be extensively validated with practical applications in real industrial contexts.

1.3 Methodological approach and scope limitations

For answering the proposed research questions, the following approach is applied:

- Since there is a large body of knowledge available both in the PSS research field and in related fields, a structured literature review was conducted on various relevant topics.
- The main research method applied is case study research. In Chapter 8, five in-depth case study reports are included, based on research performed with manufacturers who currently have a product-centric business model, but who would like to gain insight into the potential benefits of a PSS. These cases emphasize various aspects of the presented methods and are – with one additional case study – employed throughout this dissertation to illustrate the theoretical constructs.

The links between the research questions and the data collection methods applied in this work are presented in Table 1.2. Detailed information on the research design and process of the case studies is provided in Chapter 2.

Table 1.2: Overview of the research and data collection methods applied to answer the research questions of Section 1.2.

Research method	**Data collection method**	RQ_1	RQ_2	RQ_3	RQ_4	RQ_5
Literature review	Online search	X	X	X	X	X
Case studies	Interviews with internal experts	X	X	X	X	X
	Interviews with (potential) customers				X	X
	Interviews with industry experts				X	X
	Focus group discussions	X	X	X	X	X
	Analysis of accounting data				X	X
	Analysis of field failure and usage data				X	X

Since the topic chosen within this dissertation is wide and multidisciplinary, a clear delineation of the scope is necessary to ensure both the cohesion and relevance of the presented discourse. Although each of the following aspects is interesting in its own right, they are considered to be out of scope for the presented work:

- The various competitive dynamics that influence the acceptance, price setting and industry structure during and after implementation of a PSS are not analyzed in detail. Such topics require a specific approach rooted in strategic management, which is not pursued here.

- Likewise, although organizational aspects and company culture are very important for a manufacturer's succesful implementation of a service based business model [72], they are not considered.
- The ecological potential of a PSS is not analyzed in detail nor quantified, although many of the cost reduction opportunities offered by a PSS (e.g. opportunities for remanufacturing and re-use) are accompanied by an abatement of energy and material resources (cfr. e.g. [200]).
- A detailed analysis of consumer behaviour and estimation of the actual willingness to pay of customers for a PSS, which are topics within marketing research, are not pursued.
- The scope is restricted to investment goods and the application of the presented theories and methods for other industries, such as consumer goods, basic materials, food, is not explored.

1.4 Main contributions

The five main contributions of this work are:

C_1: A novel functional decomposition technique *Functional Hierarchy Modeling (FHM)* that allows to analyze and represent the function(s) of an investment good on different levels of abstraction is presented in Chapter 4.

C_2: A PSS definition, representation scheme and typology are presented in Chapter 5. These three elements provide a proposed theoretical basis for PSS research.

C_3: Three complementary approaches for PSS ideation are presented and illustrated in Chapter 6.

C_4: A methodology to analyze the innovation potential of a PSS in cost reduction and value increase is presented in Chapter 7.

C_5: The applicability of this methodology on industrial case studies is extensively demonstrated in Chapter 8.

1.5 Structure of the dissertation

This dissertation is structured as follows:

- In Chapter 2 some background is presented on case study research in general and on its application in the PSS research field in particular. The research design, process and quality of the case studies included in this dissertation are discussed.
- Chapter 3 lays out the theoretical foundations for the next chapters. It includes the following sections:
  - Section 3.1 describes how the business model of a manufacturer of investment goods can be described comprehensively and unambiguously.
  - Section 3.2 presents a critical review of existing PSS definitions and typologies.
  - Section 3.3 discusses the interpretation of cost and value in the context of this dissertation and presents background on cost assessment methods that are applied later in Chapter 7 and 8.
  - Section 3.4 first presents the four basic mechanisms that determine the business potential of a PSS for a manufacturer of investment goods. Subsequently, a detailed review of available theories, methods and tools for the economic evaluation of a PSS is presented. This review allows to position the proposed methodology of Chapter 7 in the state of the art.
- Chapter 4 presents Functional Hierarchy Modeling (FHM), a novel theoretical framework that allows to analyze and represent the function(s) of an investment good on different levels of abstraction. FHM is the foundation for the PSS typology presented further on.
- Chapter 5 proposes a new definition, a representation scheme and a typology of PSS. These three elements constitute a theoretical foundation for PSS research.
- Chapter 6 presents three approaches that can be applied to support PSS ideation (i.e. the generation of PSS ideas). At the end of this chapter, a variety of PSS options that were derived for five of the cases introduced in Chapter 2 are presented.
- Chapter 7 presents a new methodology to assess and analyze the business potential of a particular set of PSS options. The business potential is

related to two of the mechanisms described in Section 3.4, namely the ability of a PSS to reduce costs and its ability to increase value.

- Chapter 8 presents the application of the methodology of Chapter 7 on five in-depth case studies introduced in Chapter 2.
- Chapter 9 summarizes and discusses the main contributions of this dissertation and suggests opportunities for future research.

An overview of this structure and its link with the research questions and main contributions is presented in Figure 1.2.

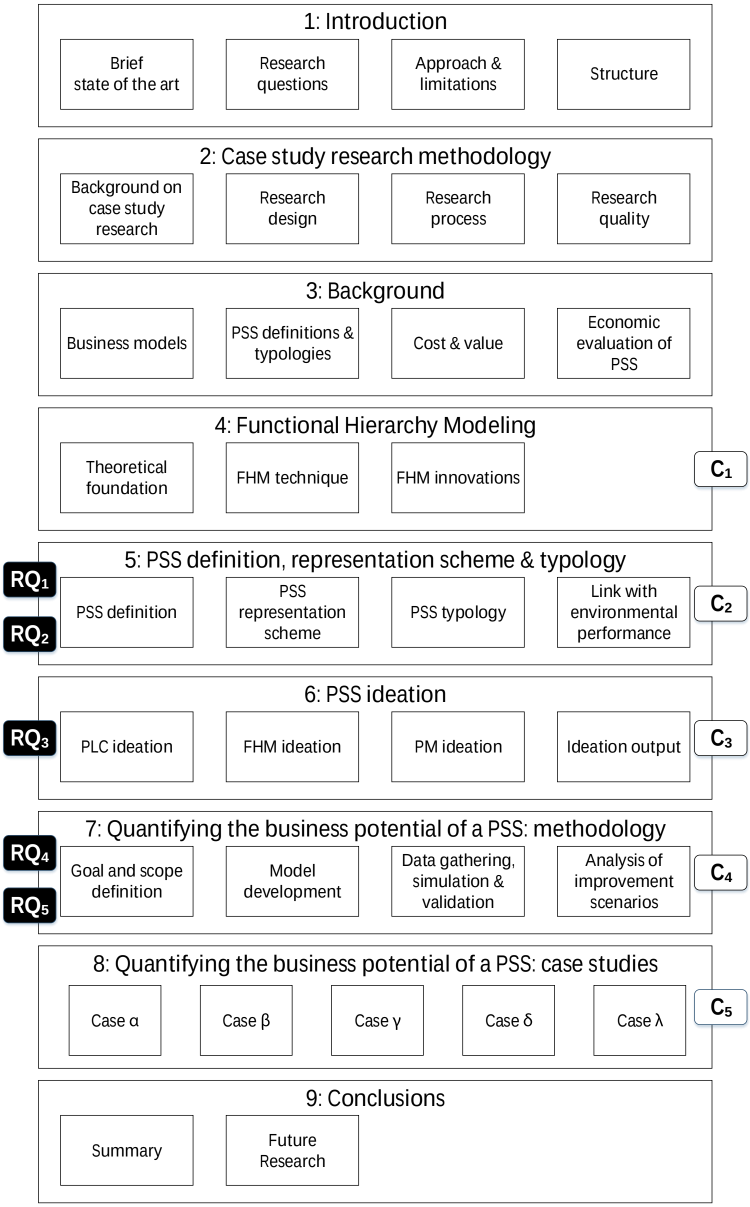

Figure 1.2: Structure of this dissertation and positioning of the five research questions RQ_i and main contributions C_i.

Chapter 2

Case study research methodology

As indicated in Chapter 1, in the presented research work the case study approach is the main research method. In this chapter, first some background is presented on case study research and specifically on its application in the PSS research field in Section 2.1. Subsequently, in Section 2.2, the research design and process are comprehensively documented and the measures taken to enhance the quality of the presented case study research are described.

2.1 Case study research and its application in the PSS field

Case study research is a qualitative research method that is widely applied in social sciences [243]. A qualitative case study is defined as an empirical research that primarily uses contextually rich data from bounded real-world settings to investigate a focused phenomenon [14]. Application of case study research in the PSS field is widespread [11], which is logical, given the fact that case study research is deemed especially appropriate to study complex phenomena in their context [243] in fields where theory and understanding are not yet well developed [61]. That this description applies to the PSS field, is characterized by Monts finding that the drivers, barriers and opportunities for companies to shift to a PSS are highly context-specific [144] and by the fact that, after almost two decades of PSS research, no unified and widely accepted definition of a PSS exists to this date (cfr. Section 1.1).

In case study research, multiple data collection methods can be used, including both qualitative approaches (e.g. interviews with company representatives) and quantitative approaches (e.g. analysis of financial data) [138]. Using multiple data sources in one case study is termed *triangulation* [14]. Case study research can be applied for different purposes: for exploration, theory building, theory testing and theory extension/refinement [230]. It is especially appropriate for answering *how* and *why* research questions [19].

Several authors criticize the lack of methodological rigour demonstrated in the application of case research in the PSS field [145, 213]. This is not an isolated phenomenon, as the same criticism is identified in other research fields, such as supply chain [183], operations [14], marketing [23] and logistics management [161]. In these articles, various measures are suggested to enhance the rigor of case research.

Most importantly, case study reports should be transparent and complete so that readers and reviewers can judge the *research quality* according to the following criteria [80, 161]:

- *Transferability* (are the findings of the study transferable to other contexts?)
- *Truth-value* (do the findings of the researcher match with the informants' realities?)
- *Traceability* (is the research process comprehensively documented?)

To safeguard the transferability of case study findings, it is important that the underlying theoretical aim, the unit of analysis, the justification of case selection and number of cases are provided [161, 183, 243]. Truth value necessitates that informants correct or confirm the interpretations developed by the researcher [161]. Traceability requires that the *case study protocol* is included, whereby information is provided on the number of informants, how they were selected and the techniques that were applied for data collection [161, 243].

2.2 Case study research design, process and quality

In the presented research work, case studies were applied for different purposes. In the description of the research questions presented in Section 1.2, it was stated that the PSS field is still in need of a sound theoretical basis. Therefore, a substantial goal of the presented research is *theory building and refinement.* All theoretical frameworks and methods put forward in this dissertation, such as Functional Hierarchy Modeling (Chapter 4), the novel PSS definition, representation scheme and typology (Chapter 5) and the approaches for PSS ideation (Chapter 6), were developed and refined during case studies focused on identifying and evaluating PSS options in an industrial context. The advantages of theory built from case studies, as opposed to theory built from incremental studies or axiomatic deduction, are, according to Eisenhardt, the increased likelihood of generating novel theory and the consistency with empirical observations [61]. Moreover, the availability of case study descriptions allows to illustrate new concepts and theories with 'real life' examples.

Besides, case study research is explicitly chosen as a research method to *test the applicability* of the methodology that is proposed in Chapter 7. This methodology corresponds to research questions RQ_4 and RQ_5 and targets the systematic identification of the business potential of a PSS. Many scholars in the PSS field suggest that multiple case studies should be used to validate the applicability of new methodologies and tools [10, 26, 33, 213]. In general, multiple case study research is considered more robust than single case study research [61, 95, 243].

All case studies that were performed in the context of the presented research concerned companies that participated in the research project BOSS[1]. BOSS was carried out by Sirris and KU Leuven, financed by IWT and ran from 2010 untill 2013 [151]. Its target group were manufacturers of investment goods headquartered in Flanders and its aim was the development of theories, methods and techniques that aid these companies in evaluating the business potential of a PSS. Out of all case studies performed within the BOSS project, six longitudinal cases were selected and are described in this dissertation. The reason why these cases in particular were selected, is discussed further on. First, the characteristics of the cases are displayed in Table 2.1.

For each case study, a central project team was assembled within the company, consisting of the company representatives of whom the job titles are mentioned in bold in Table 2.1. These company representatives were appointed by the companies themselves. In the focus group meetings with the central project team, each of which typically lasted two to four hours, the progress of the case study was discussed, feedback was gathered and decisions were made for the next phases. The numbers of such meetings held for the different cases and the total timespan between the first and the final meeting are described in Table 2.2. Additionally, meetings were held with external stakeholders (cfr. Table 2.2). *Triangulation* was achieved by using various data collection methods during the

[1] Acronym for *Business Opportunities in Service Systems*

Table 2.1: Main characterics of the case study companies.

Case	Type of product	Description/ main activities of the company	Job titles of company representatives involved in the case study	External stakeholders involved in the case study
α	Traction elevators	Manufactures elevators, provides support, maintenance and renovation services	**Service manager**, **Business development manager**, R&D professional, Service technicians	Technical responsible in a university hospital, Cleaning responsible in a university hospital
β	Lighting control systems[a]	Designs and implements automatic lighting control systems and provides maintenance and support services	**Business unit director**, Project manager	Installation technician, Lighting industry specialist
γ	Fire detection systems	Implements fire detection systems on a project basis and provides maintenance, inspection and renovation services	**Marketing manager**, **Operations manager**, **Service manager**, Installation project leader, Marketing project leader	Two fire insurance specialists
δ	Diamond polishing systems	Develops technology for the diamond gemstone industry	**Director**, **Technical advisor**, Design engineer	Representatives of diamond processing companies , industry specialist, representative of diamond transportation company
λ	Wind turbine gearboxes[b]	Designs and manufactures gear boxes for the wind power industry	**Service manager**	Representatives of providers of condition monitoring systems
ω	Optical sorting machines	Designs and manufactures optical sorting machines and provides maintenance, upgrading and training services	CEO, CTO, CFO, **Service manager**, **Project manager**	Recycling expert

[a] Part of this case study was carried out as a master thesis project within the Master of Engineering program at KU Leuven.

[b] This case study was carried out as a master thesis project within the Master of Industrial Management program at KU Leuven. The focus of this case study was the quantification of the additional value of a condition monitoring system for a wind turbine gearbox and as such it illustrates certain methodological aspects of the methodology of Chapter 7.

case studies. The data collection methods applied include focus group meetings, interviews with internal and external experts and the processing of field failure data, usage data and accounting data. All specific information sources for each case are detailed in Chapter 8 and in Appendices B to E.

Table 2.2: Characteristics related to the timespan and the number of meetings performed in the case studies.

Case	Total number of project team meetings	Meetings about quantitative methodology	First meeting	Final meeting	Additional meetings with external stakeholders
α	11	8	March 2010	May 2011	3
β	8	6	March 2010	Dec. 2011	2
γ	11	6	Feb. 2010	Dec. 2012	2
δ	8	5	March 2011	Nov. 2012	6
λ	3	3	Nov. 2009	Sept. 2010	1
ω	6	0	June 2010	Jan. 2012	1

As can be seen in Table 2.2, most case studies focused on the application of the quantitative methodology of Chapter 7. *The main goal of the case studies was to test the applicability of this methodology in an industrial setting.* The *unit of analysis* is one individual firm. Rather than following the methodology linearly, the actual research process included returning to previous phases based on insights gained later within the same case study or derived from other cases. Such an iterative procedure is a typical phenomenon in case study research [183]. In between the project meetings, data gathering and analysis activities were performed and reports with intermediary results were prepared to be discussed at the next meeting. After each meeting, a report with the main conclusions and action points was prepared and distributed among the central project team.

The number of case studies selected can be justified as a trade-off between two contrasting objectives. On the one hand, it is considered crucial to present enough detailed, in-depth information on each individual case to enhance the traceability of the presented research. On the other hand, for increasing the transferability of the methodology presented in Chapter 7, the cases were selected such that they are representative for a large share of the target group (i.e. manufacturers of investment goods) and such that they provide contrasts that help to attain a better understanding of the applicability of the methodology. The representativeness and the ability to provide contrasts can be judged based on the characteristics provided in Table 2.3. As can be seen from Table 2.3, the selected cases cover a large variety in the different dimensions displayed. Case ω is not included in this table, since in this case study, the methodology of Chapter 7 was not applied. Case ω is included to illustrate some of the theoretical constructs of Chapters 4, 5 and 6.

Table 2.3: Characteristics of the case studies in terms of the representativeness for the target group.

Case	**What carries the largest share of the initial investment value?**	**What are the key value aspects? (cfr. Section 7.2.5)**	**What are the key cost components?**	**Degree of maturity of the central technology**	**Level of customization**
α	Central product	Productivity, safety, assurance	Maintenance, energy, cleaning, logistical costs	Mature	Highly standardized system
β	Initial service for implementation/ commissioning/ fine-tuning	Flexibility (savings in external energy costs), productivity, convenience	Initial engineering, implementation, customizing	Rather immature	Highly customized system
γ	Decentralized product	Safety, assurance, responsiveness	Revision, installation, maintenance costs	Rather mature	Highly customized system
δ	Central product	Productivity, responsiveness, safety	Operation, consumables	Immature	Highly standardized system
λ	Central product	Productivity	Maintenance	Rather mature	Highly standardized system

The case studies are presented anonymously in this dissertation due to confidentiality restrictions. However, the transparancy of the presented case study research is safeguarded by providing enough information in this chapter, in Chapter 8 and in Appendices B to E such that the quality of the research can be judged based on the three main dimensions transferability, truth-value and traceability. Several measures were taken to safeguard the quality of the presented research in these three dimensions. They are listed in Table 2.4.

Table 2.4: Measures taken to safeguard the research quality, whereby in the three last columns a marker indicates a positive influence on the transferability (TF), truth-value (TV) and traceability (TC) of the presented research.

Measures	TF	TV	TC
Information on the theoretical aim, the unit of analysis, the justification of the number of cases and the case selection is provided in Section 2.2	x		
During the meetings of the central project team, informant feedback was gathered, in order to compare the findings of the analyses performed by the authors with the insights of the company representatives. These meetings were documented and reports were distributed.		x	x
The results from the case studies were presented at the steering committee meetings of the BOSS project, where about 15 company and industrial sector organization representatives were present and provided feedback on the presented results. These meetings were all documented.	x	x	x
Multiple data sources were used within each individual case study, and extensive validation was performed, as documented in Chapter 8.		x	
Informants are described in Table 2.1.			x
Data collection techniques are documented in Chapter 8			x
The sections of Chapter 8 that contain the final reports of the case studies were reviewed by the company representatives involved in that particular case.		x	

2.3 Conclusions

In this chapter, some background was presented on case study research in general and specifically on its application for PSS research. A shortcoming of many case study descriptions in PSS research is a lack of methodological rigor, which can be avoided by comprehensively documenting the research design, process and the measures to enhance the research quality in three dimensions: transferability, truth value and traceability. In Section 2.2, the case studies performed within the presented research were introduced and described accordingly.

Chapter 3

Theoretical background

With the research questions of Section 1.2 in mind, this chapter presents the theoretical background related to the following topics:

- Business models (Section 3.1)
- Product-Service Systems (PSSs) (Section 3.2)
- Cost and value (Section 3.3)
- Economic evaluation of PSS (Section 3.4)

3.1 Business models

If a manufacturing company adopts a PSS, it does not only change its offering. It changes the core logic of how it creates and captures value, or, in other words, it alters its business model [122]. Therefore, the PSS concept is closely related to the notion of a corporation's *'business model'*, a popular research topic in the literature on Strategy, Management and Information Systems. Some scholars even describe a PSS as a 'function-oriented business model' [187, 211]. In this section, some insights are extracted from the literature on business modeling and a decomposition of business models into building blocks is proposed.

The following key features of a business model are relevant for our discourse:

- Although there is no generally accepted definition of the term *'business model'* [147], in our view the following one is adequate: *a business model describes the rationale of how an organisation creates, delivers and captures value* [158] [1].
- A business model is essentially a conceptual, rather than financial, model of a business and is more generic than a business strategy [204].
- Many authors view a business model as a multidimensional concept, which can be decomposed into several *'atomic elements'* or *'building blocks'*. Several decompositions into building blocks have been proposed (most of them are reviewed in references [12] and [160]). The most popular of these decompositions in the practioner literature is the *business model canvas* of Osterwalder et al. [158].

Based on existing business model ontologies ([12, 27, 157, 158]) we propose a comprehensive decomposition of a business model specifically for manufacturers of investment goods. In this decomposition, a business model consists of twelve building blocks that are grouped into four domains (cfr. Figure 3.1):

1. In the **customer domain**, a business model consists of *value propositions* targeted towards *customer segments* through *distribution channels*.
2. In the **technological domain** the physical architecture of a business model is described by specifying *internal systems* of the investment good, its main *functions* and the *external systems* in its physical environment.
3. In the **organizational domain**, a business model consists of *strategic resources* that are brought, through the company's *processes*, to the *value network*.
4. In the **financial domain**, a business model encompasses the company's *cost structure*, its *revenue mechanism* and the distribution of *risks and investments* among the actors of the value network.

A formal description of each of these building blocks is provided in Table 3.1.

[1] Since *value* is used as explanans in this definition, it should be properly defined. This will be done in Section 3.3.

Table 3.1: Business model decomposition for investment good manufacturers adapted from existing business model ontologies [12, 27, 157, 158]

Customer domain	
Value Propositions	The bundles of products and services that create value for specific customer segments [158]
Distribution Channels	The means of reaching out to the customer segments [94] (e.g. through a complex system of intermediaries)
Customer Segments	The homogenous groups of (potential) customers
Technological domain	
Internal Systems	The investment good's main subsystems and components
Functions	The investment good's main functions
External Systems	The most important products and systems that are interfaced to the investment good at certain moments along its lifecycle
Organizational domain	
Strategic resources	The key assets, capabilities, firm attributes, information, knowledge, etc. controlled by a firm that enable it to conceive of and implement strategies that improve its efficiency and effectiveness [13]
Processes	The main processes within the company to create, deliver and capture value
Value Network	The description of the web of relationships that generates both tangible and intangible value through complex dynamic exchanges between two or more individuals, groups or organizations [3]
Financial domain	
Cost Structure	The description of which resources (e.g. labor, materials, energy) are consumed by which actor of the value network to obtain the investment good's functionality.
Risks and investments	The manner in which the most important potential future losses and investments are assigned amongst the actors of the value network.
Revenue mechanism	The architecture of the revenue streams [39], that determines how the company makes money from selling its offerings.

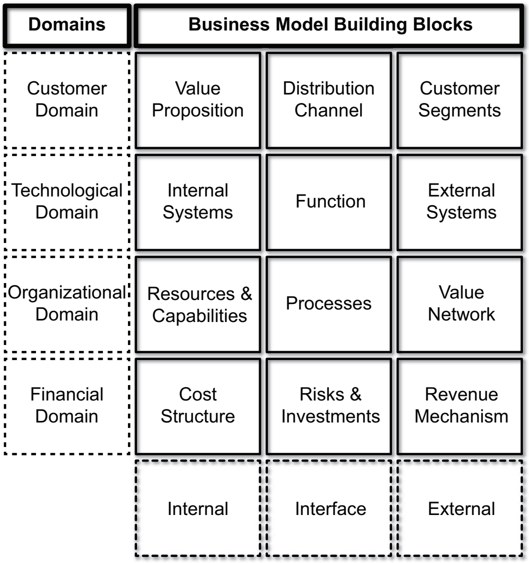

Figure 3.1: Business model decomposition for investment good manufacturers.

Within each domain, there is an internal, an external and an interface-related building block. In the customer domain, value propositions are created internally and interfaced through distribution channels to external customer segments. In the technological domain, the investment good consists of internal systems interfaced through their functions to external systems. In the organizational domain, internal strategic resources are converted through the company's processes to an external value network. In the financial domain, costs occur internally, revenues have external sources and at the interface of financial relations risks and investments are distributed amongst actors. Two examples of this decomposition logic are presented in Figure 3.2. These descriptions of the business models of a manufacturer of optical sorting equipment and an elevator manufacturer were developed during discussions with representatives of company α and ω.

During most of the case studies introduced in Chapter 2, the business model decomposition of Figure 3.1 was applied to gain a first insight into the company's activities and environment. The exact link between the concepts *business model* and *Product–Service System* will be clarified in Section 5.1.

Domains	Business Model of an elevator manufacturer		
Customer Domain	**Value Propositions** - New elevator - Maintenance contracts - Modernization	**Distribution Channels** - Direct sales - Public tender - Sales through project developer	**Customer Segments** - Office buildings - Industry - Residential - Hospitals - ...
Technological Domain	**Internal Systems** - Drive system - Display and control - Lighting - Car and doors	**Functions** - Safety - Efficiency - Comfort	**External Systems** - Elevator shaft - HVAC - Electrical power - Fire detection system
Organizational Domain	**Strategic Resources** - Installed base in Belgium and Northern France - Customizable design	**Processes** - Engineering - Sales - Installation - Maintenance - ...	**Value Network** - Building owner - Engineering firm - Certification agency - Architect - User
Financial Domain	**Cost Structure** - Manufacturing & Assembly - Energy (Active+ Passive) - Maintenance & Repairs - Cleaning - Periodical certification	**Risks & Investments** - RISKS: project delay, changing legislation, ... - INVESTMENTS: elevator, maintenance fleet, help-desk,...	**Revenue Mechanisms** - Payment schedule depending on date of commissioning - Yearly payment for maintenance (and repairs)

Domains	Business Model of a manufacturer of optical sorting machines		
Customer Domain	**Value Propositions** - New machine + installation - Spare parts - Temporary rental - Training - ...	**Distribution Channels** - Direct (key accounts) - Through agents	**Customer Segments** - Food - Tobacco - Recycling
Technological Domain	**Internal Systems** - Optical system - Electronics - Electrical - Mechanical - Interfaces	**Functions** - Food safety - Quality - Productivity	**External Systems** - Packing machines - Cutting machines - Washing machines - ...
Organizational Domain	**Strategic resources** - Optics knowhow - Application knowledge	**Processes** - R&D - Sales - Service - Production - Project Management	**Value Network** - Customer - Consumer - Legal authority - Agent - ...
Financial Domain	**Cost Structure** - Installation - Energy - Maintenance & Repair - Insurance product liability - ...	**Risks & Investments** - RISKS: claims, changing legislation, product loss - INVESTMENTS: machines, material stocks, building,....	**Revenue Mechanisms** - Payment per machine - Payment per intervention - Payment per upgrade - Payment per training

Figure 3.2: Highlights of the business model decomposition of Figure 3.1, applied for a manufacturer of elevators (company α) and a manufacturer of optical sorting equipment (company ω).

3.2 Product–Service Systems (PSSs)

In this section, we will review existing PSS definitions (in Section 3.2.1) and PSS typologies (in Section 3.2.2).

3.2.1 PSS definitions

As mentioned in Section 1.1, no unified and widely accepted definition of a PSS exists to this date. Given the large variety of PSS definitions available in the academic literature (e.g. [10, 26, 76, 126, 142, 150, 176, 212]), the last thing the PSS field seems to need is yet another candidate. But unfortunately, as we will see, none of the available definitions is able to describe the essence of the PSS concept in a parsimonious and unambiguous way.

It is generally agreed that all theory building must start with 'good' definitions [231, 232]. Wacker presents eight rules that formal conceptual definitions should respect [231], described in Table 3.2.

Table 3.2: Eight rules for a 'good' formal conceptual definition [231].

Rule 1:	Primitive and derived terms should be used *(replaceability)*.
Rule 2:	Each concept should be uniquely defined *(uniqueness)*.
Rule 3:	Vague or ambiguous terms should not be used *(clarity)*.
Rule 4:	Definitions should have as few as possible terms *(parsimony)*.
Rule 5:	Formal conceptual definitions should be as similar as possible between studies *(similarity)*.
Rule 6:	Definitions should not expand current definitions and make them broader and less precise *(precision)*.
Rule 7:	Definitions should not introduce new hypotheses *(unbiasedness)*.
Rule 8:	Content validity must be checked empirically after the formal conceptual definition passes the first seven rules *(content validity)*.

Rule 8 refers to empirical tests that are used to ascertain whether the formally defined concept is able to sample the conceptual domain [231]. A pragmatic interpretation of this rule that we apply here, is a combination of two *acid tests* to check whether the PSS definition allows to sample the PSS conceptual domain:

- *Rule 8a:* All examples of Table 1.1 should fit in the PSS definition. We presume, based on a review of the literature on PSS, that there is a widespread agreement among PSS scholars that these classical PSS examples are to be considered as such.

- *Rule 8b:* We consider a fictitious example that in our view should not be regarded as a PSS, since it corresponds completely to a traditional product-based business model. Suppose a manufacturer sells a machine tool for €100.000, in an integrated package with an installation service valued at €200. If a definition would consider this example to be a PSS, in our view, it is too broad for our purposes.

In Table 3.3, a selection of the most commonly cited PSS definitions is presented. One recently published definition, which was derived from a structured literature review, is added [26]. In the last column, the rules that are violated by the proposed definitions are highlighted.

Table 3.3: A selection of PSS definitions and the rules of Table 3.2 that they violate.

Author	**Proposed definition of a PSS**	**Violated rules**
Goedkoop [76]	A marketable set of products and services capable of jointly fulfilling a users need	2, 8b
Mont [144]	A system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models	4, 6, 7, 8a
Baines [10]	An integrated offering of products and services that delivers value in use	2, 8b
Boehm [26]	An integrated bundle of products and services which aims at creating customer utility and generating value	2, 3, 4, 8b
Meier [135]	An Industrial Product-Service System is characterized by the integrated and mutually determined planning, development, provision and use of product and service shares including its immanent software components in Business-to-Business applications and represents a knowledge-intensive socio-technical system	4, 6, 7, 8a

As can be seen from Table 3.3, the rules violated by the existing PSS definitions are diverse:

- *Rule 2* states that each concept should be uniquely defined such that it can easily be discerned from related concepts and that no *concept-stretching* [231] should be allowed. The definitions of Goedkoop [76] and Boehm [26] stretch the PSS concept in so far that it cannot be discerned from a *value proposition* in general (cfr. the definition provided in Table 3.1). Baines' definition also stretches the PSS concept by posing that any bundle of products and services that has a value in use[2] is a PSS.

- *Rule 3* prohibits the use of vague or ambiguous terms. As we will see in Section 3.3, *value* (used in Boehms definition [26]) is a term with many meanings and no clarification is provided in [26] how this term is to be interpreted[3].

- *Rule 4* demands parsimony and corresponds to Occam's razor: *entia non sunt multiplicanda praeter necessitatem*[4]. For our purposes, Monts [142] and Meiers [135] definitions are too verbose and complex. Boehms definition [26] uses both *customer utility* and *value* although these terms overlap semantically.

- *Rule 7* prohibits including hypotheses in definitions. In Monts definition [142], the notion that a PSS is designed to have a lower environmental impact is a hypothesis. Many authors acknowledge that the ecological performance of PSS should not be taken for granted (e.g. [213]).

- Our pragmatic *Rule 8a* is not problematic for most PSS definitions, since they are too broad or imprecise not to consider the examples of Table 1.1 as a PSS. Only Monts hypothesis that a PSS is designed to have a lowered environmental impact could exclude for example Rolls-Royces *Power-by-the-Hour* model or Arcomets offering, because there is no proof of environmental incentives in the development of these models. Meiers definition [135] can be interpreted as excluding some PSS examples of e.g. Arcomets offering because it does not include software.

- In our view, our pragmatic *Rule 8b* demonstrates that many of the existing PSS definitions are too broad. Our example of a machine integrated with a (relatively insignificant) installation service is a PSS according to the definitions of Goedkoop [76], Baines [10] and Boehm [26].

In conclusion of the previous argumentation, it can be stated that according to Wacker's rules, the PSS concept is still in need of a good formal conceptual definition. A novel PSS definition will be proposed in Chapter 5.

[2]Value in use expresses the utility of some particular object [235], cfr. Section 3.3.

[3]In Section 3.3 clarification will be provided on how value, as used in this dissertation, for example in RQ_5, is to be interpreted.

[4]Things should not be complicated more than necessary.

3.2.2 PSS typologies

Besides PSS definitions, the academic literature suggests different PSS typologies[5]. Here, one specific categorization of PSS into three types seems to be generally accepted and is widely used (e.g. [10, 83, 144]):

- In a **product-oriented PSS** ownership of the product is transferred to the customer, but the provider sells additional services (*Type 1*).
- In a **use-oriented PSS** ownership remains with the provider and usage rights are sold to the customer (*Type 2*).
- In a **result-oriented PSS** the product's functional results are sold, that directly fulfill customer needs (*Type 3*).

This typology discerns PSS based on the following distinguishing features:

- The allocation of property rights of a product, which discerns Type 1 from Type 2 and 3
- The provider's role in the value production, which is restricted to offering usage rights in Type 2 and expanded to offering functional results in Type 3.

The main purpose of a typology is *"to furnish a means by which concrete occurrences can be compared [...] and comprehended within a system of general categories"* [134]. Typologies should be parsimonious and simple [8] , but, on the other hand, they should not be too simple, and capable of capturing the richness of the empirical entities under study. *"Typologies do not make assertions and therefore cannot be judged 'right' or 'wrong'. [...] Like tools they may be judged or found more or less useful for a particular purpose"* [127].

The usefulness of a PSS typology in particular depends on its ability to explain the essence of the PSS concept, as many scholars use the classical trichotomy for this purpose (e.g. [10, 41, 198, 212]). Thus the impression has emerged that retaining property rights by the PSS provider is an essential characteristic of any advanced form of PSS (i.e. Type 2 or 3). On the other hand, the PSS typology is often applied to describe a variety of PSS options within a particular industry or for a particular manufacturer (e.g. [212, 234, 242]). Manufacturers interested in a PSS model might come to the conclusion that no PSS options within the use- and result-oriented type exist without retention of ownership.

[5]This section was published as Section 1 of reference [221].

This impedes the advancement of the PSS concept, as several authors indicate that the financial risks associated with ownership retention and consumers' lack of enthusiasm about ownerless consumption are important barriers to its implementation [10, 21, 233].

In our view, the classical PSS typology is subject to three main problems that prevents it to capture the complexity of PSS examples found in practice:

1. A **first problem** is caused by the fact that the allocation of property rights is chosen as the distinguishing feature between PSS types. Although this choice easily allows to discern classical use-oriented PSS examples (such as leasing, rental or sharing models) from product-oriented PSS types, in reality it is often too strict. A number of PSS examples exist that certainly have a use-oriented logic, but do not involve ownership retention by the provider. For example, Rolls-Royces *Power-by-the-Hour* model is often presented as a use-oriented PSS [10, 206], although in reality the ownership of the aircraft engine does not remain with Rolls-Royce. Either it is transferred to its customers, the airlines companies, or to a lessor [11]. Thus, if the classical PSS typology is to be applied strictly, this example should in principle be regarded as a PSS Type 1 and not as a Type 2, although a substantial part of the revenues for the provider are generated on a usage defined basis. In fact for many products, and investment goods in particular, due to the capital requirements and risks involved, it is not feasible that manufacturers would retain the property rights of all their products, but this does not prohibit the existence of a strong use- or result-oriented logic in their offerings. If the current PSS typology would be applied strictly, these cases would never be considered Type 2 or 3. This suggests that many PSS examples would remain 'stuck' in the first type, which is confirmed in the study of Lim et al., who have analyzed 181 published PSS cases and found a large majority (123) belonging to the product-oriented type, which is far more prevalent than the use- or result-oriented type [118].

2. A **second problem** with the prevailing typology is that it does not distinguish between two different types of PSS: a PSS in which a customer pays for the hours that the product is being used (a fee per operational hour) and a PSS in which a customer pays a fixed fee per elapsed time period that the product is available (a fee per available hour), although both models are essentially different in terms of the incentives for the provider to optimize the availability of the product and in terms of the risks involved. For example, a machine supplier that is paid per hour that his machine is operating at the customer's site, will have to consider and control all external factors that could lead to downtime (e.g. material

shortages, technical failures of peripheral equipment), while, if the supplier is paid per hour that the machine is available at the customer's site, these factors will be of lesser importance. Not only is the distinction between these two models not made, the terms 'use-oriented' and 'availability-oriented' PSS are often treated as synonyms [10, 135].

3. A **third problem** is that the prevailing typology is not sufficiently refined to distinguish between different types of result-oriented PSS. The result-oriented PSS type is claimed to *'directly fulfill customer needs'* or to *'provide functional results'* although both concepts (needs and functions) are quite problematic to express unambiguously in concrete terms [211]. Functions, for example, can be expressed on different levels of abstraction, in an objective or a subjective manner and either in terms of the effect that a product has on its environment or in terms of device-specific parameters [38, 64]. Consider as an example possible PSS models under which a radiator could be sold. On the lowest level of abstraction, a radiator's function is to *'transfer heat between water and the air through a conducting surface'* and its functional result could be expressed in terms of the heat transfer efficiency, e.g. as the *Equivalence of Direct Radiation (EDR)*, a standardized metric for quantifying the output ability of space-heating radiators. On a higher level of abstraction, a radiator's function is to *'keep the room temperature in a specific building compartment near a set point'* and the functional results on this level can be expressed in terms of its ability to keep the room temperature within specified bounds (e.g. 20 ± 2 °C). On an even higher level of abstraction, a radiator's function is to *'provide thermal comfort to building occupants'*, which is a direct fulfillment of a human demand. One example of a result-oriented PSS would imply that a space heating solution is sold based on promising a certain heat transfer efficiency during a period of ten years, whereby the supplier can choose the types of radiators used (e.g. size, material, shape) and will provide the cleaning, maintenance and repair services necessary to maintain the promised EDR. Another result-oriented PSS type could mean that the supplier promises to provide a certain level of thermal comfort for the building occupants during a period of ten years, taking into account the diverse factors that contribute to the attainment of these functional results (e.g. the building insulation, ventilation, humidity, . . .). In the classical PSS trichotomy, both examples would end up in the same category of *'result-oriented PSS'*, although the huge difference between these PSS-models is evident.

In conclusion of the previous arguments, it can be stated that the prevailing PSS typology does not allow to capture the multiplicity and nuanced differences that exist between different PSS options in practice. The main reasons for these shortcomings are to be found in the choice of the distinguishing features between PSS types, that emphasize on the allocation of property rights, and in the fact that the notion of *function* is not systematically treated in the available PSS literature, although orientation towards the provision of *function* is an essential characteristic of a PSS [142, 212]. Therefore, a systematic discourse on the notion of function in the context of PSSs is presented in Chapter 4 and a refined PSS typology is presented in Chapter 5.

3.3 Value and cost

For the evaluation of the business potential of a PSS, the notions *value* and *cost* are instrumental. In Section 3.3.1, we discuss their interpretation in the context of this dissertation. In Section 3.3.2, cost assessment methods that will be used later on are briefly introduced.

3.3.1 Interpretation of value and cost

Value is not an unequivocal term. Several value concepts can be distinguished, such as the following [28, 238]:

1. The *value-added* concept is defined from the provider's perspective. It assumes that value is added to a product/service offering by the provider, and thus that the offering is a container of value [238]. This interpretation is critized mainly because it underestimates the customer's role in assessing and in co-creating the value of a product/service offering [224].

2. An alternative understanding of value is that it is the *economic worth of a customer* from a provider's perspective. This interpretation, also termed Customer Lifetime Value [20], is not further explored in our exposition.

3. In Value Engineering, the value of a product is defined as the ratio of its function to its cost [139]. Value can thus be increased by adding functionality or by reducing cost. This approach is not further explored here, as we discern cost from value.

4. A fourth interpretation of value is that it is the *economic worth of a product/service offering* from the customer's perspective. Although evaluating this economic worth is far from evident, especially in a B2B context it might be feasible to evaluate the economic impact that a product/service offering has on the customer's operations [238]. While

this definition assumes that value can be expressed in monetary terms, it is critized for being to restrictive [238]. It does not allow to take intangible value aspects (e.g. brand name) into account, that are not easily expressed in monetary terms.

5. *Exchange value* is the monetary amount realized at the moment of exchanging a good or service and thus corresponds to price or the customer's *actual willingness-to-pay (WTP)* [28].

6. *Use value* or *value-in-use* is determined in relation to the customer's use situation[6]. Use value is a subjective notion and perceived by customers in relation to their demands [28]. It corresponds to the *maximum willingness-to-pay (WTP)*, the monetary amount a customer is willing to pay, in case no competing offerings exist, but within budget constraints and with consideration of other purchasing opportunities [28, 86].

Our interpretation of value combines the fourth and sixth concept. Value is the maximum WTP and is customer-dependent, i.e. it is determined in relation to the customer use situation. But, due to the focus on investment goods, this maximum WTP often corresponds to the economic impact that this investment good has on the customer's situation. For example, the value of a lighting control system is mainly determined by the lighting energy cost that can be saved. The value of a machine tool is mainly determined by the revenue that a customer can generate by using it. Therefore, in Chapters 7 and 8, special attention is paid to assessing the economic worth of an investment good for the customer in specific use situations. If a quantification in monetary terms is not feasible, we will consider value to be a multidimensional construct, in line with other approaches (e.g. [214, 248]).

We relate value to the concepts cost and price through the *value-price-cost framework*, which was originally proposed as a bargaining model by Tirole [208], and is often employed in the strategy literature [85, 86]:

- *Value* corresponds to the customer's maximum willingness-to-pay (WTP) (cfr. sixth interpretation).
- *Price* refers to the actual WTP of the customer (ideally, otherwise it is set too low). It is determined by the specific competitive environment in which the business transaction takes place.
- *Cost* reflects the consumption of resources, such as labor hours, materials and energy [62].

[6]Presumably the first author to distinguish use value from exchange value was Aristotle. Famous successors were Adam Smith and Karl Marx.

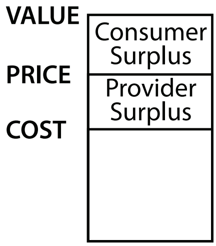

Figure 3.3: Value-price-cost framework (after [208]).

According to this framework (Cfr. Figure 3.3), value minus price is the so-called '*customer surplus*', price minus cost reflects the profit margin of the provider or the so-called *'provider surplus'*. Both surpluses should be positive for a sustainable business situation.

3.3.2 Cost assessment

The purpose of a cost assessment is to assign a monetary measure for the consumption of resources to particular *cost objects* (the units for which a cost measurement is required, e.g. a product, service, customer or project). In this section, two cost modeling techniques that will be applied during the quantitative evaluation of PSS are briefly introduced: *Time-Driven Activity Based Costing (TD-ABC)* and *Life Cycle Costing (LCC)*.

Time-Driven Activity Based Costing

Activity Based Costing (ABC) is a management approach that was introduced in the 1980s by Cooper and Kaplan [43]. Its basic principle is that resources are consumed by activities, and these activities can in their turn be assigned to cost objects. To assign resources to activities, *resource drivers* are introduced (e.g. the number of labor hours per activity). Activities are assigned to an appropriate cost object by determining *activity drivers* (e.g. the number of maintenance activities per machine per year). ABC is particularly appropriate to assign costs that are considered 'fixed' overhead costs in traditional costing systems accurately to the right cost object [99].

TD-ABC is a refinement to ABC by Kaplan and Anderson that overcomes some of the shortcomings of the traditional method: its high resource intensity, its use of subjective and costly-to-validate time allocations and the difficulties to maintain and update models [98]. TD-ABC uses *time equations* to estimate the time required for a particular activity and determines the cost per time unit of a certain resource center (e.g. a maintenance department). The number of activities can be reduced in TD-ABC in comparison to traditional ABC by applying conditional logic in time equations [68]. Consider the example that the time for preventive maintenance of a machine at the customer's site is normally 15 minutes, but 25 minutes should be added to this if the customer belongs to the petrochemical industry, due to time lost for accessing the site. Then the time required for the activity *perform preventive maintenance* can be modelled as follows:

$$\text{Maintenance time per product per intervention} = 15 + 25_{\text{if petrochemical}}$$

Thus, the creation of two different activities is avoided and the complexity of the cost model can be reduced. The logic of TD-ABC is applied in the cost models that will be discussed in chapters 7 and 8.

Life Cycle Costing

'Life Cycle Costing' (LCC) is a method that facilitates comparative cost assessments over a long time period, taking all relevant economic factors into account, including initial capital investments as well as future operational costs [6, 239]. LCC was introduced as a procurement tool in the U.S. Department of Defense in the 1960s and has been extensively applied since then in many sectors, particularly in the construction, aviation and defense sectors [6].

The basic construct in LCC is the *Product Life Cycle (PLC)*, that spans chronologically all activities throughout a product's physical life, from its conception until its disposal into waste streams [103]. The PLC consists of four phases: design, production[7], use and End-Of-Life [6]. Typically in an LCC analysis the PLC is decomposed into a *Cost Breakdown Structure (CBS)*, a tree structure that breaks down the total cost in categories up to a certain level of detail. As an example, a generic CBS is presented in Figure 3.4.

For each cost component, an appropriate cost estimation method should be chosen. Such methods can be categorized as intuitive, analogical, parametric or analytic [47]. A parametric method uses a parametric relation to derive a *top-down* approximation of a cost, while an analytical method (e.g. ABC) analyzes the cost *bottom-up* up to the smallest detail [172]. As we will see in the case studies, in practical applications often a combination of both approaches is required.

[7]This phase refers to the production of the investment good itself, not (e.g. in case of a machine tool) to the phase in which it is used to produce.

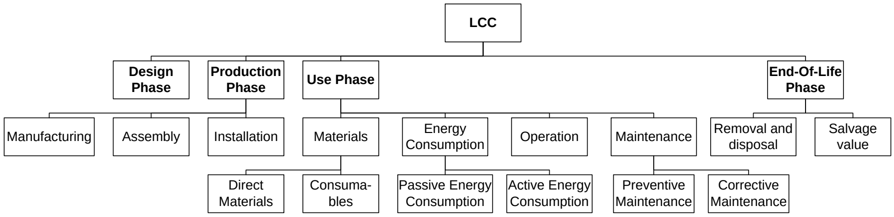

Figure 3.4: Generic Life Cycle Cost Breakdown Structure.

Different financial metrics can be used in an LCC analysis. Most commonly, the *Net Present Value (NPV)* is used [6, 123]. NPV allows to calculate costs in their present worth, taking the time value of money into account. The LCC of a series of costs C_0, C_1, C_2, ..., C_N occuring in successive years is thus expressed as:

$$NPV_{LCC} = \sum_{j=0}^{N} \frac{C_j}{(1+i)^j}$$

whereby N is the time horizon of the LCC study (e.g. 20 years) and i is the discount rate, that determines the balancing of costs that occur now and in the future. An appropriate choice for a discount rate is the company's *Weighted Average Cost of Capital (WACC)*; the rate that the company is expected to pay on average to its providers of capital (debt and equity holders) [62].

Alternatively, LCC can be expressed as an *Equivalent Annual Cost (EAC)*. This requires that all costs over the study period are aggregated as a Net Present Value and subsequently distributed as a constant cost EAC_{LCC} over all the years:

$$EAC_{LCC} = \frac{NPV_{LCC}}{\frac{1-(1+i)^{-N}}{i}}$$

An important challenge in an LCC assessment lies in determining how one should cope with all relevant risks and uncertainties in the input parameters that influence the analysis. Erkoyuncu et al. categorize uncertainties in the context of industrial PSS as *aleatory* (that cannot be reduced through further study) or *epistemic* (that can be reduced through further data or understanding) [65]. Different methods can be applied to take risks and uncertainties into account ([6, 62, 172]):

- A ‘traditional’ *sensitivity analysis* calculates how the LCC evolves as a function of the variation of a single input parameter, under ceteris paribus assumption (i.e. all other inputs are kept at a constant value).
- *Scenario analysis* defines a set of scenarios based on dominant uncertainties in the input parameters, and the LCC for each scenario is calculated.
- In *Monte Carlo simulation*, statistical distributions are used to represent the uncertainties and risks of the inputs, and the statistical distribution of the output LCC is determined by running a number of simulations (e.g. 5000), whereby during each simulation run a sample is drawn from all input distributions and the corresponding output is calculated. With the current computational power of personal computers, Monte Carlo simulation can be applied easily in a spreadsheet environment, by using statistical software add-ins such as Oracle Crystal Ball™, ModelRisk™or @RISK™. Through Monte Carlo simulation, a sensitivity analysis can be performed whereby the evolution of the output LCC as a function of a single input parameter is analyzed, taking into account the variation of all other inputs.

Although over the past decades a lot of research work has been published on various aspects of LCC techniques, important challenges remain in this research field. Korpi and Ala-Risku performed an extensive review of LCC case studies published in academic and practitioner literature [111]. They conclude that most reported applications were ‘far from ideal’, assessing costs only from a limited number of PLC phases and using merely a deterministic approach in half of the cases. In their article on cost estimation for industrial PSS, Erkoyuncu et al. state that there is *“limited research that considers the in-service phase in a holistic manner by taking an activity-based approach to model the service delivery”* [65]. In their review of the cost engineering research field, Xu et al. indicate that there is a “*lack of research emphasis on the ‘in-service’ stage, in particular on the transformation from product to PSS*” [241].

3.4 Economic evaluation of a PSS

The shift from product manufacturer to PSS provider can be motivated by evaluating the economic benefits of a PSS. In Section 3.4.1, we discuss the nature of these potential benefits from a theoretical perspective. Subsequently, in Section 3.4.2, we critically review available theories, methods and tools for the economic evaluation of PSS.

3.4.1 Economic evaluation of a PSS: Theoretical background

In theory, in accordance to the resource-based view of the firm, the adoption of a PSS is an interesting option for an investment good manufacturer if this would contribute to the establishment of a 'sustained competitive advantage', which can be defined in terms of improving efficiency (reducing cost) and effectiveness (increasing value) [13]. In practice, a PSS is interesting from that manufacturer's perspective if it allows him to attract new profitable customers with the PSS or to improve the profitability of existing customer contracts. In both cases, the business potential of a PSS depends on the provider surplus (Cfr. Section 3.3.1). In essence, there are four elementary mechanisms that determine this provider surplus and thus the business potential of a PSS (Cfr. Figure 3.5):

1. *Mechanism 1: Cost reduction.* A PSS could allow to lower the cost of delivering an offering to existing customers by achieving a higher resource efficiency. In her review of existing Swedish PSS cases, Mont has found that a potential *reduction of costs associated with function provision* is a key driver for companies to develop a PSS [143].

2. *Mechanism 2: Value increase.* A PSS could allow to increase the price for existing customers because more value can be delivered (i.e. the offering can be 'differentiated' [154]).

3. *Mechanism 3: Changes to the competitive environment.* Even if no additional value is offered, a PSS could allow to increase the price for existing customers by changing the company's competitive environment (e.g. by 'locking in' customers or by 'locking out' competitors, cfr. [154]).

4. *Mechanism 4: Customer base expansion.* A PSS could allow to enlarge the profitable customer base through one of the previously described mechanisms (i.e. by lowering cost, increasing value or changing the competitive environment). By offering a PSS, a company can gain access to new customer segments, for example by lowering investment barriers for customers.

Two important remarks should be formulated at this stage:

- These four mechanisms are not mutually independent, but can reinforce each other. For example, by increasing the customer base (Mechanism 4), the competitive environment can be altered (Mechanism 3), or the cost to cater existing customers can be reduced (Mechanism 1) through economies of scale.

- It is often mentioned in literature that a PSS can have a significant *innovation potential* [135, 146, 211]. This innovation potential arises from the fact that a PSS shifts responsibilities from the customer to the provider and gives the latter more degrees of freedom in coming up with an optimal solution for the customer's demands [142]. Giving more degrees of freedom towards the PSS provider can lead him to drive down the cost or to increase the value for existing customers. For example, customers might lack the skills and resources required to keep a specific production machine in optimal working conditions, resulting in financial losses (e.g. production scrap, downtime, high repair costs). If a PSS is adopted and the machine is sold per hour of use or per delivered output within specifications, operational and maintenance-related responsibilities are (partially) shifted towards the provider. Through a combination of operational (e.g. improved maintenance diagnosis) and technological changes (e.g. reliability enhancements), these losses might be reduced. Aggregated, this potential reduction of losses represents the PSS innovation potential in this particular case. *Thus, the innovation potential of a PSS is mostly related to Mechanisms 1 and 2.* This corresponds to the main finding stated by Baines et al. [10] that *"the PSS logic is premised on utilizing the knowledge of the designer/manufacturer to both increase value as an output and decrease material and other costs as an input to a system".*

If the business potential of a PSS is to be investigated comprehensively, all four mechanisms should be taken into consideration. Ideally, a quantitative

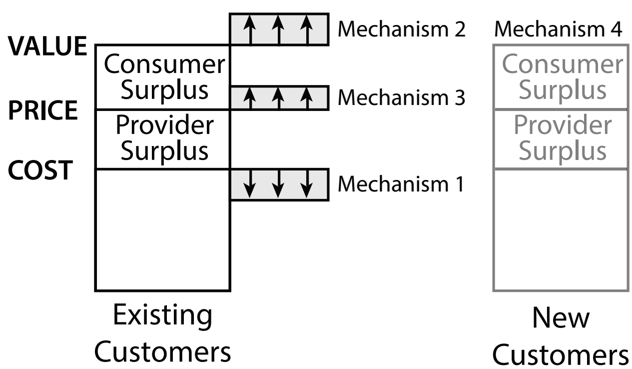

Figure 3.5: The four mechanisms that determine the business potential of a PSS

method would become available that allows to estimate exactly at what cost and at what price existing customers could be catered with a PSS, how many additional customers could be attracted through a PSS and which profits these new contracts would generate for the provider. But trying to derive a reliable quantification of all influencing factors is an arduous task. Estimating ex ante how much additional value could be offered or what costs could be reduced requires the investigation of changes to the current way of working, subject to many uncertainties and risks. Moreover, forecasting all the effects that the introduction of a PSS would have in a market for which it currently does not yet exist, is complicated by unpredictable market dynamics. It is interesting to see how current approaches deal with these difficulties and on which of the identified mechanisms they focus. This topic is discussed in the next section.

3.4.2 Economic evaluation of a PSS: Review of the available literature

In this section, a review of methods, tools and theories that are relevant for the economic evaluation of PSS is presented. The objective of this review is to summarize the existing approaches, as well as to identify their main strengths and limitations with regard to research questions RQ_4 and RQ_5. The results of an extensive search of scientific databases, enhanced with relevant approaches mentioned in review articles [10, 135, 145, 211, 233] were included. Most selected articles were published in peer reviewed scientific journals, but some conference papers and research reports were chosen as well. After filtering the results, 18 approaches were retained (presented in Table 3.4), all published in the period 2005-2013. All articles mentioned in Table 3.4 propose or apply an approach for the economic evaluation of PSS, but the presentation of this evaluation method is not always their primary purpose. The main goal and characteristics of each approach is described in Table 3.4.

These approaches were characterized according to the following criteria (cfr. Table 3.5):

- **Perspective.** Is the evaluation performed from the perspective of the PSS provider, of the customer or from both?
- **Type of article.** Is the article mainly a theoretical contribution, a description of a method or a description of case study results[8]?
- **Type of evaluation criteria.** Evaluation criteria can be qualitative, quantitative, or a combination of both. In the case of qualitative criteria,

[8] If a method description is purely theoretical, it is only categorized as ‘method description’.

judgments are typically made on a series of ordered semantic values (such as ‘very low, low, neutral, high, very high’). Quantitative criteria can be monetary, non-monetary (e.g. time units or the number of occurrences of a certain event) or a combination of both.

- **Phase.** In which phase of the ‘PSS development cycle’ is the economic evaluation to be performed? The phases are demarcated as in reference [212] (page 396-397): preparation and introduction, analysis of PSS opportunities, PSS ideation, PSS design and implementation planning. Also the phase ‘demonstration’ has been added, considered appropriate if the approach is mainly designed to demonstrate the economic benefits of an existing PSS.
- **Uncertainties and risks.** Does the approach account for uncertainties and risks?
- **Innovation potential.** Is the PSS innovation potential (Section 3.4.1) taken into account in the evaluation?
- **Mechanisms.** Which of the mechanisms described in Section 3.4.1 are taken into account?
- **Basis of evaluation.** What is the basis for the evaluation?
- **Case studies.** Are any case studies presented (none, one or multiple)?

In Table 3.6, the main strengths and limitations of the proposed theories, methods and tools are listed. Special attention is given to whether the approach's transferability is verified (i.e. its applicability in multiple contexts). The following conclusions can be drawn:

- The majority of the approaches aim to estimate the economic benefits of a PSS from the customer's perspective (8/18) or from a combined perspective customer-provider (7/18).
- Most approaches are designed to support the phases PSS design (7/18), analysis of PSS opportunities (6/18), or PSS ideation (4/18).
- Seven approaches aim to evaluate customer value, but value is only rarely expressed in monetary terms (only in reference [168]).
- The investigated mechanisms (cfr. Section 3.4.1) are primarily value- and cost-related (9/18 and 7/18 respectively), but only one combines both [107]. Three approaches [169, 217, 244] are concerned with evaluating how the potential customer base could grow (only one is quantitative, though: [244]). None of the approaches takes changes in the competitive environment into account.

Table 3.4: Overview of the 18 PSS evaluation approaches included in the review.

Approach	**Short description of the presented method, tool or theory**	**References**
Akasaka et al.	Qualitative evaluation tool of PSS ideas	[1]
Azarenko et al.	Cash-flow evaluation of PSS options for one particular case, a grinding machine.	[7]
De Coster	Theoretical framework for collaborative forecasting of PSS	[52]
Erkoyuncu et al.	Theoretical exposition on the topic uncertainty within PSS cost estimation	[65]
Geng et al.	A new importance performance analysis approach for customer satisfaction evaluation supporting PSS design, using Dematel method, vague set theory and Kanos model.	[74]
HiCS	Validation of life-cycle economic benefits of partner based solutions, developed within the HiCS project.	[67, 205, 212]
Kimita et al.	Cost evaluation method for service design, based on activity based costing	[107]
Kuo et al.	Simulation of system cost for photocopiers under a procurement or rental business model	[114]
Mannweiler et al.	Evaluation method to compare PSS variants on the basis of life cycle cost indicators	[125]
MePSS	Comprehensive PSS development method, includes economic assessment in worksheet 15 (Screening the system's profit dynamics)	[212, 217]
Omann et al.	Multicriteria tool for evaluating the impacts of PSSs, including an economic dimension	[156]
Rese et al.	Combined net present value and real options analysis to improve lifecycle management	[168]
Rese et al.(2)	Theoretical evaluation system of flexible PSS alternatives based on customers' preference drivers	[169]
Sakao et al.	Value based evaluation method for PSS using design information	[175, 121]
Shimomura et al.	Service evaluation method based on quality function deployment and the Dematel method, to quantify the importance of functional properties	[185]
Sundin, Lindahl et al.	Description of PSS case studies with quantification of their LCC and LCA performance in comparison to regular product sales	[120, 200, 201]
Tukker et al.	Qualitative evaluation of the business potential of 8 generic PSS types, not applied to a specific case	[211]
Yoon et al.	Evaluation method for designing a new PSS	[244]

Table 3.5: Characterization of the 18 PSS evaluation approaches.

Approach	Perspective	Type of article	Evaluation criteria	Phase	Uncertainties	Innovation potential	Mechanisms	Basis of evaluation	Case studies
Akasaka et al.	both	method description	quantitative non-monetary	PSS ideation	no	no	2	PSS idea	one
Azarenko et al.	both	case study description	monetary	opportunity analysis	no	no	1	firm	one
De Coster	customer	theoretical	qualitative	opportunity analysis	no	no	2, 4	firm	none
Erokyuncu et al.	provider	theoretical	quantitative monetary	preparation & introduction	yes	no	1	firm	none
Geng et al.	customer	method description	quantitative non-monetary	PSS design	yes	yes	2	PSS quality attribute	one
HiCS	provider	theoretical	quantitative monetary	opportunity analysis	no	yes	1	functional unit	one
Kimita et al.	both	method description	quantitative monetary for cost, non-monetary for value	PSS design	no	no[a]	1,2	service function	one
Kuo et al.	provider	case study description	quantitative monetary	opportunity analysis	yes	no	1	firm	one
Mannweiler et al.	customer	method description	quantitative, non-monetary	PSS ideation	no	no	1	PSS idea	one
MePSS	both	method description	mostly qualitative, some quantitative monetary	PSS design, PSS ideation	no	no	2,4	firm	mutiple
Omann et al.	both	method description	qualitative	opportunity analysis	no	no	none	PSS idea	multiple
Rese et al.	customer	method description	monetary	PSS design, opportunity analysis	yes	no	2	customer	one
Rese et al. (2)	customer	theoretical	qualitative	PSS design	no	no	2	customer	none
Sakao et al.	customer	method description	quantitative non-monetary and monetary[b]	PSS ideation	no	yes	2	customer	one
Shimomura et al.	customer	method description	quantitative, non-monetary	PSS design	no	no	2	functional property	one
Sundin, Lindahl et al.	customer	case study description	quantitative monetary	demonstration	no	yes	1	functional unit	multiple
Tukker et al.	both	theoretical	qualitative	demonstration	no	no	none	PSS type	none
Yoon et al.	both	method description	mainly qualitative	PSS design	no	no	4	region in Korea	one

[a] Although in the conclusion of this article it is stated that the method could be used for finding cost improvement opportunities, their systematic identification is not demonstrated

[b] Evaluation criteria are PSS price, value level (percentage) and investment efficiency (ratio)

- The basis of evaluation is diverse. There are approaches that evaluate the economic benefits per customer, per PSS idea, per functional unit, on the level of the provider firm, etc.
- Surprisingly, the innovation potential of a PSS is only taken into account in a minority of the approaches (only in [74, 120, 175, 205]).
- Only three approaches [74, 168, 205] allow to model related risks and uncertainties within the evaluation. None of them applies Monte Carlo simulation methods for this purpose. Erkoyuncu et al. [65] provide a theoretical description on how uncertainty should be addressed for PSS cost estimation.
- Overall, there is a limited verification of the transferability of the described approaches. Most approaches present a single case study (11/18), while only a few present multiple application examples (3/18).

In conclusion, it can be stated that despite the fact that a large variety of approaches is available, none of them allows to quantify the PSS innovation potential in both cost reduction and value improvement, accounting for all relevant risks and uncertainties. Thus, such a method would be a valuable addition to the state-of-the-art. Particular attention should be paid to verifying its transferability by demonstrating it on multiple case studies.

Table 3.6: Main strengths and limitations of the 18 PSS evaluation approaches included in the review.

Approach	Strengths	Limitations
Akasaka et al.	allows to evaluate PSS ideas quickly, with a relatively simple method, such that a PSS provider's limited resources are optimally assigned to certain PSS ideas	• innovation potential and uncertainties not taken into account (2) • limited verification of transferability (2) • only non-monetary criteria (2)
Azarenko et al.	allows to visualize the provider's cash flows over a certain time period	• innovation potential and uncertainties not taken into account (2) • limited verification of transferability (2)
De Coster	discusses forecasting approaches for 3 generic revenue streams: new product sales, PSS and consultancy	• innovation potential and uncertainties not taken into account (2) • this is a theoretical approach that is not applied/directly applicable on a particular case (2)
Erokyuncu et al.	provides a categorization of service uncertainties and applicable methods	• this a theoretical review on uncertainty within PSS cost estimation, not a method to quantify the business potential of a PSS (2)
Geng et al.	allows to estimate customer satisfaction with key PSS quality attributes such that improvement scenario's can be identified	• PSS quality, which is related to customer value, is expressed in non-monetary terms (2) • limited verification of transferability (2) • cost perspective for the provider not included (2).
HiCS	allows to visualize whether a PSS has a cost innovation potential	• uncertainties not taken into account and limited verification of transferability (2) • restricted to cost focus (2) • the proposed methodology can only reveal whether a PSS is a 'step in the right direction'.
Kimita et al.	combined cost and value assessment	• innovation potential and uncertainties not taken into account (2) • limited verification of transferability (1,2)
Kuo et al.	proposes criteria on how to compare a procurement and rental model through simulation	• innovation potential not taken into account (2) • restricted to home/office electronics and to limited PSS types (1,2) • limited verification of transferability (2)
Mannweiler et al.	allows to derive a ranking of specific PSS options from which the customer can select the one with the lowest LCC	• innovation potential and uncertainties not taken into account (2) • limited verification of transferability (2) • restricted to cost focus (2)
MePSS	proposes use of the 'profit pool' concept to evaluate a PSS's business potential	• innovation potential and uncertainties not taken into account (2)

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Table 3.6 (Continued):Main strengths and limitations of the 18 PSS evaluation approaches included in the review.

Approach	Strengths	Limitations[9]
Omann et al.	muticriteria evaluation of ecological, economic and social dimension of a PSS	• innovation potential and uncertainties not taken into account (2) • not useful for quantifying the business potential of a PSS (2)
Rese et al.	allows to estimate how a customer will value a PSS, taking into account the flexibility due to changing customer requirements over the PSS lifecycle	• cost perspective not taken into account (1, 2) • disadvantages connected with the ROA approach, specifically its complexity (2) • PSS innovation potential not taken into account (2)
Rese et al. (2)	identifies 9 generic customer preference drivers that allow to understand why a particular customer would choose a particular PSS	• innovation potential and uncertainties not taken into account (2) • this approach is theoretical, the business potential of a PSS cannot be quantified in monetary terms (2) • no verification of transferability (1,2)
Sakao et al.	design information and customer budget taken into account	• cost perspective for the provider not included (1, 2) • limited verification of transferability (1,2)
Shimomura et al.	allows to derive a ranking of functional properties based on their contribution to customer value	• innovation potential and uncertainties not taken into account (2) • limited verification of transferability (2)
Sundin, Lindahl et al.	combined economic and environmental assessment to demonstrate the performance of a particular existing PSS	• restricted to cost focus (2) • uncertainties not taken into account (2) • existing PSS is compared with traditional sales in terms of LCC performance, does not allow to estimate the innovation potential ex ante (2)
Tukker et al.	generic theoretical approach	• no verification of transferability (2) • coarseness of evaluation criteria (2) • innovation potential and uncertainties not taken into account (2)
Yoon et al.	allows to estimate the number of customers willing to accept a PSS	• innovation potential and uncertainties not taken into account (2) • disregards competitive environment (1,2) • limited verification of transferability (1,2)

[9] (1) = as identified by the author(s) of the article/report (2) = as identified during review

3.5 Conclusions

This chapter presented the theoretical foundations for the next chapters. In Section 3.1 the concept 'business model' was characterized and a generic description of business models for manufacturers of investment goods in four domains with twelve building blocks was presented. The exact link between the concepts business model and PSS will be clarified after the novel PSS definition is proposed in Chapter 5.

As argued in Section 3.2, the PSS research field is still in need of a good formal conceptual definition. Moreover, the traditional, commonly cited PSS typology suffers from a variety of problems that impede its usefulness and thus needs to be revised. Thus, research questions RQ_1 and RQ_2 are justified.

In Section 3.3, our understanding of the concepts cost and value was clarified, and two cost assessment methods that will be applied in Chapter 7 and 8, TD–ABC and LCC, were described.

Finally, in Section 3.4, the four essential mechanisms that determine the business potential of a PSS were introduced (cost reduction, value increase, changes to the competitive environment and customer base expansion) and eighteen theories, methods and tools for the economic evaluation of PSS were critically reviewed. None of the available approaches allows for an ex ante quantification of the PSS innovation potential in both cost reduction and value improvement, while taking into account the relevant risks and uncertainties. Thus, no adequate answer could be found for research questions RQ_4 and RQ_5 in the current state of the art.

Chapter 4

Functional Hierarchy Modeling

In this chapter[1], a novel theoretical framework is presented: *Functional Hierarchy Modeling (FHM)*. FHM allows to analyze and represent the function(s) of a system on different levels of abstraction and is specifically aimed at manufacturers that are interested in shifting towards offering a PSS. The *system* consists of the product they manufacture in their current business model, possibly supplemented with some basic services, such as a warranty assurance for a given period. Based on the FHM framework, a refined PSS typology is proposed in Chapter 5, better suited to explain the essential characteristics of the PSS concept and to distinguish a comprehensive set of PSS options for the manufacturer.

This chapter is organized as follows: Section 4.1 presents the theoretical foundation of FHM. It starts from a systematic treatment of the notion *function* within the engineering sciences and translates the main insights of diverse streams of research to the context of PSS. In Section 4.2 the FHM technique is presented and illustrated with several examples. Innovations in the FHM are discussed in Section 4.3 and the conclusions of this chapter are formulated in Section 4.4.

[1]Most of this chapter was published as Section 3 of reference [221] – some figures and examples were added.

4.1 Theoretical foundation of FHM

This section lays out the theoretical foundation for FHM and is organized as follows:

- The general properties of the concept *'function'* are described in Section 4.1.1.
- The representation of functions within hierarchical models is discussed in Section 4.1.2.
- The notions *functional performance* and *functional results* are defined in Section 4.1.3.

4.1.1 General properties of the 'function' concept

Function is an important concept within the engineering sciences that is intuitively understood as the expression of a system's *intended purpose* [102]. Since Product-Service Systems entail a focus on the delivery of function, it is necessary to gain a clear understanding what is meant with this term. Function can be characterized by the following statements:

- *Functions* form a bridge between the *subjective realm* of human needs (or demands) and the *objective realm* of physical artifacts [38, 64, 109]. They express why these artifacts are used and therefore constitute in essence a teleological interpretation [64].
- *Function* is closely related to *behavior* and *structure*. While a function describes why a system is used, its behavior describes how its functions are achieved – through which inputs, outputs and processes – and its structure describes the system's organization in space, i.e. its physical build-up [38, 141].
- Functions are often represented as a verb-noun pair in the form of *'to do something'* [139], possibly supplemented with contextual information. The formulation of a function chosen here is consistent with this approach: '*do something (within a context)'*.
- The same function can be achieved by different systems and a system can have more than one function.
- Functions can be assigned not only to physical artifacts, such as products or components, but also to services, activities and processes, i.e. to any type of solution.

- Functions can be defined from two different viewpoints: in terms of the effect that the system has on its environment (the so called environment-centric definition or *function as effect*) and in terms of the attributes of the specific solution that is used to carry it out (solution-centric definition). Also a mixture of both viewpoints is possible: some functions are stated in a combination of solution- and effect-related terms [38].

- The function of a system can be described on different levels of abstraction. A more abstract formulation of function will be more environment-centric, i.e. will take a greater distance from the particular solution employed to reach the desired effect, while on a lower level of abstraction a more solution-centric description can be found, stated in parameters of the solution. For a radiator, *'transfer thermal energy between a liquid and the surrounding air through a contact surface with a certain minimal Equivalence of Direct Radiation (EDR)'* is a less abstract, more solution-centric formulation of its function than the expression *'keep room temperature near a set point'*, which is a purely environment-centric definition. The first expression employs parameters of the solution, related to its internal configuration [38] (i.e. it specifies that space heating radiators should be used and describes a minimal EDR) while the second expression is stated in terms of the effect on the environment (i.e. the temperature in the surrounding room). In between pure solution-centric and pure environment-centric functions, hybrid formulations of the system's function can be established as well, that have both environment- and solution-related parameters. For example, the function of a space-heating radiator could also be stated in terms of the characteristics of the thermal field around the radiator.

The last characterization of function introduces the topic of Section 4.1.2: how functional expressions on different levels of abstraction can be presented in hierarchical structures.

4.1.2 Functional hierarchies: part-whole versus means-end

One of the basic ways to model a complex system is through the construction of hierarchical structures, in which it is decomposed into subsystems through some relation and these subsystems are further decomposed until the lowest, arbitrarily chosen level is reached [189]. Functional models often take the form of a hierarchy [64]. FHM, the technique proposed in Section 4.2, is inspired by existing hierarchical techniques, which are briefly discussed here.

Hierarchical techniques are characterized by the type of relation between parent function and subfunction(s) employed. Two basic types can be discerned: *part-whole relations*, in which the subfunctions on the lower level of abstraction are a partial refinement of the parent function, and *means-end relations*, in which the parent function is an end for which the means, the subfunction, is employed. A means-end relation is also known as a 'why-how relationship': the parent function indicates why the subfunction should be realized and the subfunction indicates how the parent function is attained. Part-whole relations, on the other hand, only explain what (the parent function is) and how (it can be refined into subfunctions), but not why [116].

Most streams of research concerned with modeling functions in hierarchical structures employ part-whole relations. This is the case for the approaches within the Engineering Design field of research, in which functional decomposition typically aids the conceptual design of products (e.g. [17], [199]). In these approaches the function(s) of the complete product are formulated at the top level of the hierarchy and decomposed top-down through part-whole relations into subfunctions on the lower levels, each of which corresponds to particular product features or components. Also the Functional Representation stream of research within Artificial Intelligence commonly applies part-whole relations for knowledge representation and automated reasoning about functions [37]. Part-whole relations are a logical choice in case the functional model aims to represent one product in particular (which is being designed or described), since they allow to associate subfunctions to structural elements within this product.

Means-end relations on the other hand are useful in linking the functions of a system to its main objectives. They start with the system under consideration and work bottom-up, whereby at each higher level of abstraction an answer to the question 'why' is required. Functional means-end decomposition is applied within the Functional Modeling stream of research, which focuses on the construction of functional models for complex technical systems (e.g. nuclear power plants), with applications ranging from fault analysis, reliability engineering to cognitive engineering [119, 141]. The most notable frameworks within the Functional Modeling stream are the Abstraction Hierarchy [155], the Goal-Tree-Success-Tree Master Logic Diagram [141] and the Multi Leveled Modeling method [119]. All these methods describe how a single function-centered hierarchy can be devised for a system that includes its objectives, functions and structural elements on different levels of abstraction. These approaches allow to formulate explicit answers to the following questions: *'Why should the system exist at all?'* and *'What can the system do?'* [93].

These questions are certainly relevant in the case of PSS, since the basic idea of PSS is an orientation towards selling function (Cfr. Section 3.2) and since developers of a PSS should look for alternative ways of function fulfillment in order to realize radical innovations [144, 211]. Notwithstanding these facts, functional hierarchies are only scarcely applied in the context of PSS. One exception is the research stream on Service Engineering, an emerging field in which engineering methods are applied for designing services [177]. Within Service Engineering, the concept *service function* has a key role and functional structures are employed to design services, according to part-whole decompositions [186]. But application of means-end hierarchies in the context of PSS is non-existent and analysis of function is nowhere related to a typology of PSS.

4.1.3 Functional performance and functional results

To express how well and in what quantity a particular function is being performed by a particular system, the concepts *functional performance* and *functional result* are deployed.

Definition 4.1. *The* functional performance *of a system describes how well its functions or intended purposes are being performed.*

Functional performance can be assessed by looking at a combination of *performance indicators.* Occasionally, one performance indicator suffices to demonstrate how successful a particular function is attained, but in most cases functional performance should be assessed according to a heterogeneous set of performance indicators. For example, a manufacturer of fire detection systems can judge the functional performance of his system according to the following performance indicators: the number of false alarms during a certain time period (e.g. one year), the probability that an occurring fire is missed by the detection system and the time between the actual occurrence of fire and moment of user notification.

Definition 4.2. *The* functional result *of a system is a standardized unit of function delivery.*

Functional result is closely related to the concept of *functional unit* within the Life Cycle Assessment literature. *"The functional unit names and quantifies the qualitative and quantitative aspects of the function along the questions what, how much, how well, and for how long"* [91]. However, they are not completely synonymous. While in the context of Life Cycle Assessment the main purpose of defining a functional unit lies in providing a basis to calculate and compare environmental impact, in the context of PSS a *functional result* is also a basis, but now one that should allow both provider and customer to assess how much functionality is being offered and that can be regarded as a unit for an economic transaction. Similar to a functional unit, a functional result should be measurable [42] and should reflect how the system is actually being used [130]. For a lighting system (including luminaries, ballasts and lamps) an example functional result is *'one year of providing light sources at specified points in a certain office building, that emit a specified level of luminous flux (expressed in lumen) during specified time windows'*. Similar to functions, functional results can be expressed on different levels of abstraction. For a lighting system, for example, the functional result could also be expressed as *'one year of providing a specified illuminance (expressed in lux) at specified task areas within a certain office building during a certain time window'*, or, on an even higher level of abstraction, *'one year of providing visual comfort for all occupants of a certain office building during the specified time windows'*.

Functional performance and functional results are related concepts. In order for the output of a certain system to be considered as a functional result, it is evaluated according to some predetermined performance indicators according to which it should attain a certain minimal functional performance. The functional performance of a system indicates how many functional results are being delivered and how well this is done. Expressing functional results on different levels of abstraction and thereby identifying different PSS types can be done through application of FHM, the hierarchical decomposition technique for PSS presented in Section 4.2.

4.2 Functional Hierarchy Modeling technique

In this section Functional Hierarchy Modeling (FHM) is presented, a technique that allows to create a model of a system that expresses the system's functions and clarifies their means-end interdependence with functions of other products, services or processes that are operational in the same customer environment. Once this FHM is constructed, it can serve as a framework for the expression of *functional results* on different levels of abstraction, that allow to distinguish between different types of PSS, as will be demonstrated in Chapter 5.

The general logic behind FHM is that it is a hierarchical model that combines three main levels within one single representation framework: customer demands, functions and structural elements (cfr. Figure 4.1):

- The **customer demands level**, situated in the subjective realm, on the highest levels of abstraction, consists of core customer demands that are related to a single overall objective. Core customer demands highlight the main *job to be done* by the system; the main reason why the customer uses it. Not all demands related to the system are included in the FHM;

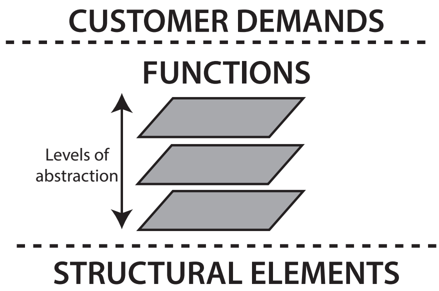

Figure 4.1: The three levels within Functional Hierarchy Modeling.

only the demands that are obligatory in order for the system to perform the main task that the customer expects it to do (i.e. those related to its *intended purpose*).

- The **functional level** contains functions on different levels of abstraction. Each function is represented as a verb-noun pair, possibly supplemented with contextual clarification. Functions on the lowest level of abstraction are expressed in terms of parameters of a specific solution employed. Functions on the highest level of abstraction are expressed in terms of the desired effect on the environment. In between both extremes, there are functions that have both effect- and solution-related parameters, or so called 'hybrid' functions (cfr. the last statement of Section 4.1.1).

- The **structural level** contains structural elements, i.e. each product, service or process that contributes to the attainment of the functions on the higher levels of the hierarchy. Each structural element can be seen as a specific solution to realize (a) particular function(s).

The main decomposition logic of FHM is depicted in Figure 4.2. The top two levels of the FHM, the demands and functional level, are organized according to *means-end* or *why-how* relations, i.e. for each lower element in the hierarchy its parent determines *why* it should be attained, while the lower element determines *how* the parent is realized (cfr. Section 4.1.2). Only within the structural level at the bottom of the hierarchy, the decomposition logic is different, and determined by *part-whole* relations, which means that each lower element is considered to be a part of its parent element.

In this section, FHM is explained from the standpoint of a company that manufactures investment goods. This company has within its product portfolio a system that represents one or more of the structural elements at the lowest

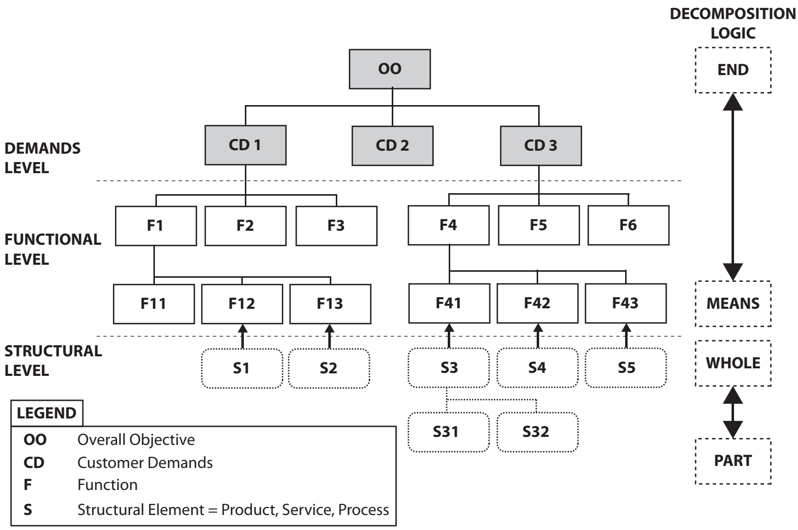

Figure 4.2: Main decomposition logic within FHM.

level of abstraction. Starting from this system, the following steps are required to construct its FHM:

1. **Determination of the scope of analysis**: first the overall objective of the system and the type of customer for which the FHM is constructed are determined

2. **Identification of core customer demands**: the overall objective is decomposed into core customer demands within the demand level of the FHM

3. **Construction of the teleological chain**: the teleological chain is constructed, that links the system of structural elements to the overall objective

4. **Construction of the full hierarchical model**: the FHM of the *as is* situation at the customer is completed by including all the other functions and structural elements in the model

The following Sections 4.2.1. to 4.2.4 elaborate on these consecutive steps with several illustrations.

4.2.1 Determination of the scope of analysis

As a first step in the modeling process the scope of the analysis should be defined: the overall objective associated with the system and the type of customer included.

The *overall objective* of the system is a single expression of its main intended purpose. It is positioned at the highest level in the FHM and should be broad enough to allow for the inclusion of all relevant factors in the analysis, but not too general, to avoid that the model becomes unduly complicated. The overall objective should be selected carefully according to the insight of the modeler, because it will determine the scope of the decomposition (cfr. [119, 141]).

For a fire detection system e.g., the overall objective was stated by the authors in consultation with the manufacturer as to *'protect people, property and buildings from fire'*. Alternatively, it could have been more generally defined as to *'protect people, property and buildings from fire, crime and work accidents'* but it was decided to omit these factors in order to limit the complexity of the modeling process and because in the underlying industrial case study the involved company is not considering to extend its activities into these domains. Therefore the added value of including them in the analysis was considered to be minimal. On the other hand, it was decided that if the overall objective would be limited to *'protect property from fire'* the resulting model would be too narrow to allow for a meaningful analysis. Thus the choice of the overall objective is highly dependent on the judgment of the modeler, but crucial for the usefulness of the resulting model.

Another explicit confinement of the analysis that should be decided in the beginning of the modeling exercise is the *type of customer* considered. The FHM represents how the functions of the system are related to the functions of other structural elements present within the customer's environment and how they contribute to the fulfillment of core customer demands. For a specific product category both the demands and structural elements employed can be fundamentally different for different types of customers. For example, a food processing company that acquires an optical sorting machine for removing contaminants out of food has completely different demands than a recycling company that acquires a sorting machine for separating different material streams out of e-waste, and thus a separate FHM seems justified for both types of application. In the case of fire detection systems, the structural elements employed to guarantee fire safety for a petrochemical plant are quite different from those required for a hotel, although their core demands (to avoid fire and to limit its impact when it occurs) are the same. Also in this example, a separate FHM is warranted.

4.2.2 Identification of the core customer demands

The next step in the construction of an FHM entails decomposing the customer's overall objective into core customer demands, the primary reasons why the customer uses the system; they are defined in terms of the core job to be performed, which can be either the avoidance of certain problems or the attainment of particular goals. Establishing the core customer demands might require contact with (potential) customers. Guidelines on how to elicit customer demand data are provided, for example, in reference [216] and, in the context of new product development, in reference [215].

It should be noted that there is no unique decomposition of an overall objective into customer demands, but nevertheless one decomposition can be more suitable than the other for the purpose of this model. This can be illustrated with the example of a fire detection system. In Section 4.2.1, its overall objective was stated as to *'protect people, property and buildings from fire'*, that can be decomposed into core customer demands in several ways. A first decomposition can distinguish the demand to prevent fire from the demand to limit the impact of fire when it occurs, and, alternatively, a second decomposition can distinguish between the demands to protect people, property and buildings. The main difference between both decompositions is that the first is based on the source of the potential problem (i.e. fire) and the second is based on the effects of this problem. Both decompositions will result in an entirely different model. A criterion on which to judge the appropriateness of one decomposition over another is the interconnectedness of functions with different core demands. Preferably, the functions are as independent as possible such that the functions realizing one customer demand have no role in the realization of another demand. This allows to limit the complexity of the resulting model and is a requirement analogous to the independence axiom in Axiomatic Design, which states that functional requirements in a design should be kept independent [199]. In the example of the fire detection system, it can be seen that the functions that realize the reduction of fire impact mostly have no role in realizing the prevention of fire occurrence and vice versa. If the decomposition would have been constructed according to the effects of fire on people, property and buildings, this interconnectedness would obviously be higher: functions that try to protect people are more intermingled with functions aiming for the protection of property. So in this example the first decomposition into customer demands is preferable.

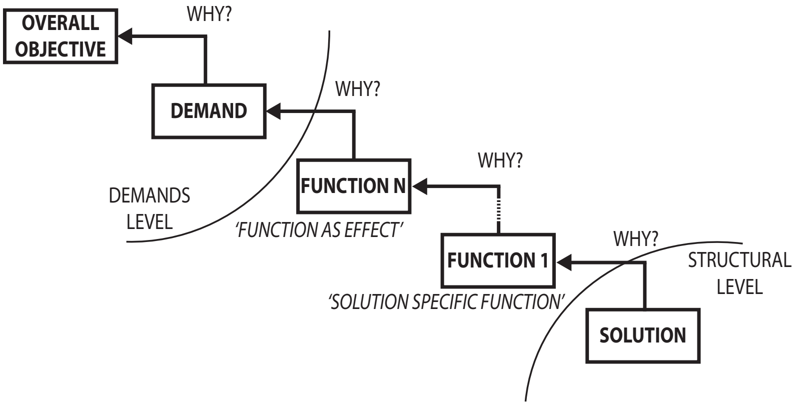

Figure 4.3: The teleological chain that connects an investment good (solution) with its overall objective.

4.2.3 Construction of the teleological chain

Once the overall objective and the core customer demands are determined, the main teleological chain or *backbone* of the FHM can be constructed by reasoning upwards from the relevant structural elements in the lowest level of the model towards the relevant demands in the demands level. Going one step upwards corresponds to answering the question *'why is this element used?'*, or, once the functional level is reached, *'why should this function be fulfilled?'* After reaching one level higher up in the hierarchy, the subfunctions or underlying structural elements can be found by formulating an answer to the question *'how is this function realized?'* or *'how is this customer demand satisfied?'* The teleological chain thus starts with the system as a solution that fulfills a certain solution-centric function (cfr. the last statement of Section 4.1.1), reasons upwards to environment-centric functions (idem) and ultimately is connected to the core customer demands and overall objective in the demands level. A generic teleological chain is represented in Figure 4.3.

The teleological chains of a space heating radiator is presented in Figure 4.4. For three additional examples, cases α, β and γ, the teleological chains are provided in Figures A.1 to A.3 of Appendix A.

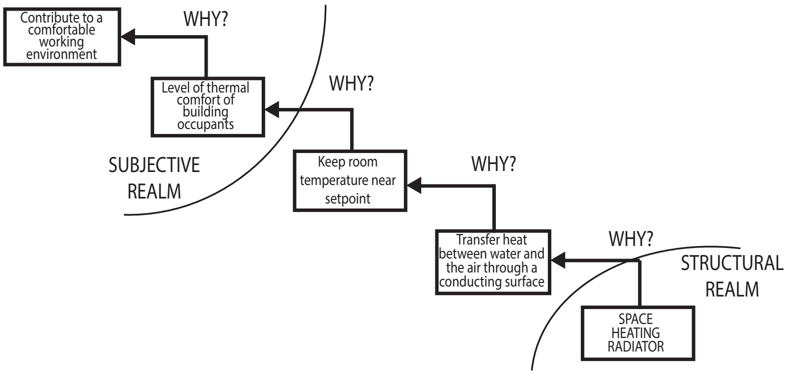

Figure 4.4: Teleological chain of a space heating radiator.

To each level of the resulting teleological chain, functional results (cfr. Section 4.1.3) can be assigned. For the different levels of abstraction in the teleological chains of the examples presented in Figure 4.4 and in Appendix A, the corresponding functional results are described in Table 4.1.

Table 4.1 demonstrates that selling functional results for an elevator, radiator, lighting system and fire detection system, such as implied in functional-results type of PSS, can be done on different levels of abstraction. Different types of PSS can be discerned based on the type of functional results offered; i.e. solution-oriented, effect-oriented or demand fulfillment-oriented. This is elaborated in Chapter 5.

4.2.4 Construction of the full hierarchical model

The teleological chain determined in the previous step forms the backbone of the FHM. It can be expanded in a full hierarchical model through the inclusion of other functions and structural elements that contribute to the fulfillment of the same core demands and overall objective. This model represents the current situation or *as is* situation; i.e. the functions and elements currently used by the customer to reach the overall objective. The main purpose of this model lies in representing the means-end logic of the current situation at the customer. All the functions are considered to be *complementary*, which means in this context that they all should be successfully performed in order to achieve the fulfillment of the parent function. In the example of a space heating radiator, the function *'keep air temperature near set point'* is to be achieved by the

Table 4.1: Functional results on different levels of abstraction for the four examples of Figures 4.4, A.1, A.2 and A.3.

Type of system	**Elevator (case α)**	**Space heating radiator**	**Lighting system (case β)**	**Fire detection system (case γ)**
Demand-fulfillment result	Provide comfortable, safe and efficient flow of building occupants during one year	Provide a guaranteed level of thermal comfort and perceived indoor air quality in building A during one year	Provide a guaranteed level of visual comfort for building occupants of building A during one year	Provide fire mitigation in building A during one year (excluding prevention)
Environment-centric functional result	Provide comfortable, safe and efficient vertical transportation of people in building A during one year	Keep air temperature at 20 $\pm$ 2°C for building A during one year	Provide a guaranteed level of task area illuminance (expressed in lux) in building A during one year	**1**. Provide protection from fire and smoke in a building during one year, by promising that their spread will not exceed a specified level. **2**. Provide a promised level of protection for building occupants from fire during one year **3**. Provide a promised level of support to fire service operations during one year
Solution-centric functional result	Provide an elevator service between specified floors of building A during one year	Provide a guaranteed heating capacity (exclusive of energy input), e.g. expressed in EDR for building A during one year	Provide a guaranteed level of luminous flux (expressed in lumen) in building A during one year	**1**. Provide fire detection during one year **2**. Provide timely notification of the emergency during one year **3**. Provide for identification of fire location during one year
Structural elements	Elevator	Space heating radiator	Luminaire, lamp and lighting control system	Fire detection system

complementary subfunctions *'control temperature'*, *'generate heat'*, *'distribute heat'* and *'transfer heat'*.

The fact that only complementary functions are considered, is a simplification of reality, since in practice other relations between elements of the hierarchy are possible as well, such as: the loss of a subfunction will only lead to the loss of the parent function after a certain time period of malfunction. But these nuances are ignored in the proposed approach. At this point, in order to represent the *as-is* situation, no alternative functions or structural elements are presented yet; this is kept for Section 4.3.

For the example of a space heating radiator, the resulting FHM is provided in Figure 4.5. For a fire detection system and a lighting system, FHMs are presented in Figures A.4 and A.5 of Appendix A. Each connection between elements in the demands and functional level within the hierarchy represents a *'why-how'* relation. The full resulting FHM clarifies how the function(s) of these systems can be expressed on different levels of abstraction and which other factors (structural elements and functions) contribute to the functional performance on each level of the hierarchy and to the realization of the overarching core customer demands.

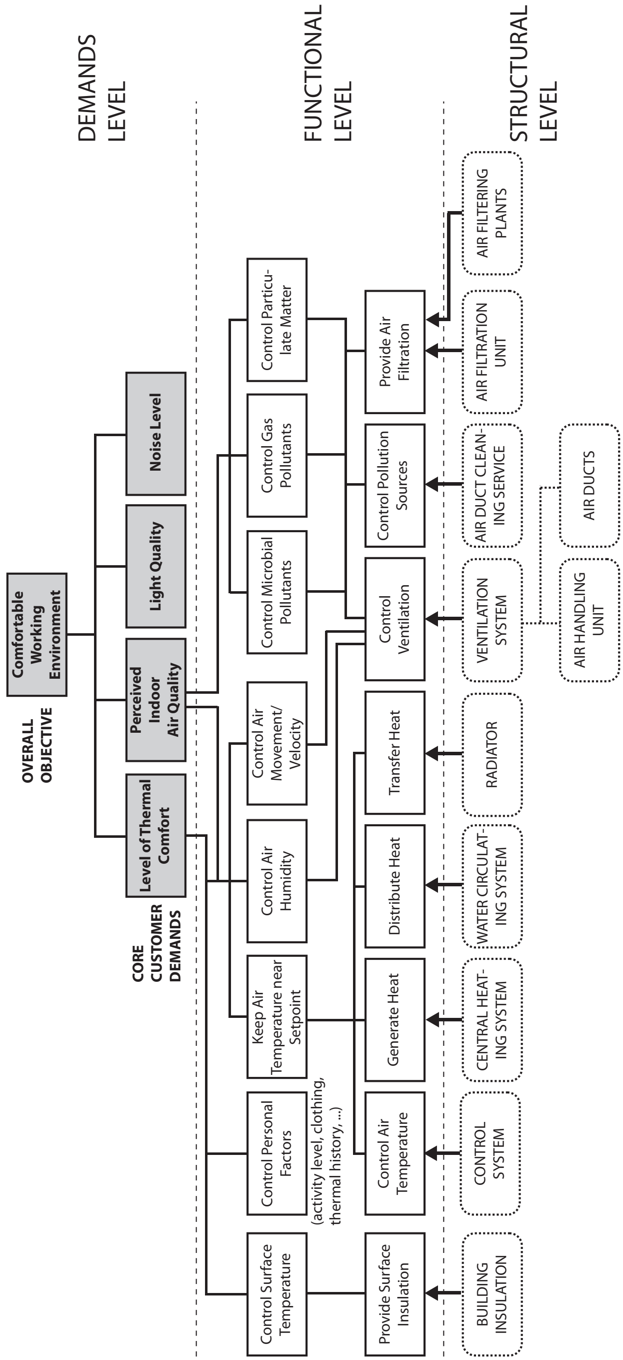

Figure 4.5: FHM of a space heating radiator.

4.3 Innovations in the FHM

The FHM offers an overview of the current (or *as is*) situation at the customer: the functions and structural elements that are currently used to fulfill a certain objective, consisting of a set of customer demands. But this as-is situation might not be the optimal arrangement on how the overall objective can be reached. Innovations in the FHM might occur according to the following general principles (illustrated with the example of the FHM of a space heating radiator, cfr. Figure 4.5):

- Some structural elements might be replaced by alternatives that are more efficient (as well economic as ecological efficiency can be considered, i.e. in terms of cost or environmental impact). For example, the function *'generate heat'* can be performed by different types of central heating systems (e.g. boilers with or without condensation) and the function *'provide surface insulation'* can be performed by different types of insulation materials.
- Likewise, some functions can be replaced by more efficient alternatives. For example, the function *'generate heat'* could be replaced by the function *'control solar heat gain'*, that implies the use of solar radiation to increase the temperature inside a building (i.e. through passive solar building design).
- Based on the current situation, some structural or functional elements within the FHM might be more efficient in fulfilling a certain parent function or customer demand than others. Priorities can be assigned according to this efficiency and based on these priorities, the role of the more efficient elements in the function fulfillment can be increased. For example, the function *'keep air temperature near set point'* might be performed more efficiently not by using an alternative heat generation system, but by using a better temperature control system. Likewise, the demand *'thermal comfort'* could be attained more efficiently, not by a better control of the air temperature, but by controlling the inside surface temperature in the building (i.e. by providing better building insulation). The fact that some structural or functional elements of the FHM can be more efficient in carrying out a certain function can even imply that other elements are not strictly necessary to achieve the same functional results. For example, with an effective combination of the functions *'control pollution sources'* and *'control ventilation'* the function *'provide air filtration'* might become redundant.

- Apart from their intended purposes (i.e. their functions), the different structural elements that are present in the customer's environment can have unintended behavior as well. Sometimes this unintended behavior can be turned into intended purpose (i.e. *function*). For example, the 'waste heat' of lights and electrical appliances in a house might be turned from an unintended side effect into a means to realize the function *'generate heat'*.

According to these principles, innovation opportunities within the FHM can be identified that allow to fulfill the same demand or function more efficiently. If one takes an element on a higher level of abstraction as the main focus for innovations, more options in the aforementioned innovative categories will be found. For example, if innovations are sought that allow to fulfill the demand *'thermal comfort'* more efficiently, there will be more options than if one is exclusively looking at innovations to fulfill the function *'generate heat'* more efficiently. This corresponds to the idea that the closer one gets to direct demand fulfillment, the more degrees of freedom exist to achieve this. In the context of Product-Service Systems, this insight has led to the conclusion that the *'functional results'* type of PSS is the one with the largest potential for environmental impact reduction [210, 211], and, as is known from Section 4.2.3 this is increasingly true for functional results associated with higher levels of abstraction in the FHM.

4.4 Conclusions

In this chapter, Functional Hierarchy Modeling (FHM) was introduced and illustrated with industrial examples. The backbone of FHM is the teleological chain that shows how the function(s) of the investment good can be expressed on different levels of abstraction and to which customer demands they are related. This teleological chain starts from the investment good, is constructed through means-end relations and reasons all the way up to the overall objective of the system. The teleological chain of the investment good can be expanded into a full hierarchical model, that clarifies which other structural elements (products, services or processes) are operating in the same customer environment and are important in realizing functional performance on the different levels of the hierarchy.

To the different levels of abstraction of FHM a variety of PSS options can be associated, as will be demonstrated in Chapters 5 and 6.

Chapter 5

PSS definition, representation scheme and typology

In this chapter, first, in Section 5.1, a new definition for PSS is proposed and evaluated according to the criteria presented in Section 3.2.1. Subsequently, based on the FHM framework developed in Chapter 4, a new representation scheme for Product-Service Systems is introduced[1] in Section 5.2 that allows to specify one particular PSS option for a manufacturer. This representation scheme contains the product and service elements of a PSS, the way they are integrated and the corresponding revenue mechanisms. These characteristics, introduced in Section 5.2, form the basis of the refined PSS typology presented in Section 5.3. In Section 5.4 the usefulness of the new PSS typology for the explanation of the essence of the PSS concept and for PSS ideation is compared with the traditional PSS typology (cfr. Section 3.2). Section 5.5 discusses the relevance of FHM and the refined PSS typology for the advancement of the PSS concept and for the environmental goals of PSS research in particular.

5.1 PSS definition

As we have seen in Section 3.2.1, there is no generally accepted PSS definition. The existing candidates are prone to various problems, that were identified

[1] Sections 5.2, 5.3, 5.4 and 5.5 were published as Sections 4 and 5 of reference [221] – some figures and examples were added.

according to Wacker's eight criteria for good formal conceptual definitions [231]. The following definition of a PSS is proposed:

Definition 5.1. *A* Product–Service System *is an integrated offering of products and services with a revenue mechanism that is based on selling availability, usage or performance.*

Definition 5.1 is discussed in light of the mentioned criteria in Table 5.1. We conclude from this table that in our view Definition 5.1 meets all of these rules. Definition 5.1 has the following implications:

- A PSS is not a type of value proposition, nor a type of business model, but a particular combination of a value proposition and a revenue mechanism. Therefore, a PSS is considered to be a subset of a business model.
- Within one business model, there can be more than one PSS. This corresponds to examples found in industry: Rolls-Royce for example offers a PSS in which overhaul and repair services are integrated and charged per flying hour and a PSS in which maintenance, repair and overhaul services are sold in an integrated offering per flying hour. Atlas Copco offers both a PSS in which a compressor is rented out (availability based) and a PSS in which it is charged per m^3 of compressed air (performance based). A specific PSS can be tailored to a specific market segment.
- While the term *integrated* refers to the value proposition, the terms *availability, usage and performance* refer to the revenue mechanism in the PSS. As will be demonstrated in the next section, they correspond to different types of revenue mechanisms.

5.2 PSS representation scheme

According to Definition 5.1, a PSS consists of an integrated offering of products and services and a particular revenue mechanism. It can be characterized by specifying:

- which product and service elements it includes (i.e. the PSS elements that constitute the value proposition)
- how these elements generate income for the provider (i.e. the revenue mechanisms)
- how these elements are integrated (i.e. the level of integration of the value proposition elements)

Table 5.1: Assessment of Definition 5.1 in light of the eight rules for a 'good' formal conceptual definition.

Rule 1 (Replaceability): The primitive and derived terms in Definition 5.1 are the following:

- *integrated*: integration of products and services means in this context that they are sold together.
- *products and services*: these terms are somewhat problematic, since *"service is embodied in the utility of material artefacts and services often need material artefacts to enable service delivery"* [41]. Services can be distinguished from products because they have an element of intangibility, because they are produced and consumed at the same time (uno actu principle) and because they involve customer contact [133, 135]. But not all scholars agree that this distinction is possible, as some argue that *"all products are services"* [84] and others that *"every service is a product"* [188]. Stahel rejects the PSS terminology because it treats products and services as separate entities, which corresponds – in his view – to the *"mind frame of the Industrial Economy"* [196]. But from a pragmatic perspective, we assume that for most readers the terms product and service are sufficiently clear to be considered primitive.
- *revenue mechanism*: this term is defined in Table 3.1 as *"the architecture of the revenue streams that determines how the company makes money from selling its offerings"*.
- *performance* is understood here in its meaning of functional performance (cfr. Definition 4.1 on page 53)

Rule 2 (Uniqueness): In our view, the proposed definition allows to delineate the PSS concept more clearly from related concepts such as *value proposition* and *business model*. While other PSS definitions (e.g. [10]) assume that a PSS is a type of value proposition, we consider it to be a particular combination of *value proposition* and a *revenue mechanism*. As such, a PSS is a subset of a corporation's *business model*.

Rule 3 (Clarity): No ambiguous or vague terms (e.g. value, utility) are avoided in Definition 5.1.

Rule 4 (Parsimony): Our definitions consists of 20 words with no semantic overlapping. This is more than the imprecise definitions of Goedkoop (14), Baines (12) and Boehm (16) but less than the definitions of Meier (31) and Mont (28).

Rule 5 (Similarity): Similarity purports that an existing, generally accepted definition should only be replaced by another definition if it is superior [231]. Since there is currently no commonly accepted definition of a PSS and since the existing definitions encompass important problems (cfr. Section 3.2.1), this criterion is fulfilled.

Rule 6 (Precision): No existing definitions are made broader and less precise.

Rule 7 (Unbiasedness): No hypotheses are introduced in Definition 5.1.

Rule 8 (Content validity): As we can see from the examples in Table 1.1 on page 2, Definition 5.1 corresponds to the way these examples are commonly presented. Information is provided on what the offering is (which products and services) and what the revenue mechanism is (how they are sold). The revenue mechanisms of these examples are either based on selling availability (e.g. Arcomet, Hilti), usage (e.g. Rolls-Royce, Xerox) or performance (e.g. Philips Lighting, Econation). On the other hand, the example of the company selling new machines integrated with an insignificant installation service is not considered a PSS according to Definition 5.1, which illustrates that unlike the definitions of Goedkoop, Baines and Boehm, Definition 5.1 is not too broad.

First, types of revenue mechanism are described according to which products, services or an integrated combination of products and services can be sold. The following types can be discerned, ordered by the level of performance orientation:

- An **input-based (IB)** revenue mechanism means that revenue is transferred from the customer to the provider according to the inputs delivered to effectuate the function of a product or service. In case of a product, this means that the property rights of the product are transferred to the customer and revenue for the product is generated at the moment of property transfer. For a service, this means that revenue is generated per intervention based on the resources necessary to deliver the service, such as labor hours or materials. In case of an input-based repair service the revenue depends on the number of interventions, working hours and materials used for the repairs.
- An **availability-based (AB)** revenue mechanism means that revenue is transferred from the customer to the provider based on the time period during which the product or service is available for the customer, independent of how much it is actually being used or delivered in that period. For a product this means a monthly rental or leasing fee and for a service this means a fixed monthly sum to be paid for which the provider promises to deliver the service to the customer whenever necessary. In the example of a repair service, a time-based revenue mechanism could mean that, in return for a fixed monthly payment, the provider will carry out all necessary repairs to keep the underlying product functioning correctly, regardless of how intensively the product is used.
- A **usage-based (UB)** revenue mechanism means that revenue is generated only during the actual usage of the product or service. Usage can be expressed in time units (e.g. flying hours for an aircraft engine), in other units that correspond to the usage dimension (e.g. kilometers for a car) or even in a combination of units (e.g. taxi metering based on as well time as distance traveled). An example of a service with usage-based revenue mechanism is an elevator repair service with a fixed sum per time unit that the elevator is actually travelling. Alternatively, another usage-based revenue mechanism for an elevator repair service charges according to the distance traveled.
- A **performance-based (PB)** revenue mechanism means that revenue is generated based on the functional performance of the product or service. Within performance-based revenue mechanisms there are three main sub-types, related to the level of abstraction within the FHM on which functional performance is defined:

- A **performance based solution-oriented (PB-SO)** revenue mechanism means that revenue is generated according to certain solution-specific functional performance indicators. These indicators are all parameters that describe the performance of the solution (i.e. system) itself and not of the environment. For a radiator, a solution-specific functional performance indicator is, for example, the heat transfer efficiency of a radiator expressed as the *Equivalence of Direct Radiation*. Thus if a space heating solution is to be paid according to a promised level of heat transfer efficiency[2] it is sold under a solution-oriented performance based revenue mechanism.
- A **performance based effect-oriented (PB-EO)** revenue mechanism means that revenue is generated according to objective environment-specific functional performance indicators. These indicators are formulated independent of the solution used and only in terms of the effects on the environment. For a radiator, an objective environment-specific functional performance indicator is, for example, the percentage of time that the temperature in a certain room is between 18 and 22°C and thus a space heating solution that promises that the room temperature remains 99,5% of the time within these boundaries, is sold under an effect-oriented performance based revenue mechanism.
- A **performance based demand fulfillment-oriented (PB-DO)** revenue mechanism implies that revenue is generated according to a subjective performance indicator that expresses how well a customer demand is fulfilled. For a radiator, such a performance indicator is, for example, the *Percentage People Dissatisfied* with the current thermal comfort level, which could be determined according ISO 10551, an international standard to assess ergonomics of the thermal environment using subjective judgment scales. If a space heating solution is sold based on e.g. a promised PPD maximum of 5% at all times, it is sold according to a demand fulfillment-oriented performance based revenue mechanism.

The level of integration of a PSS determines which PSS elements are integrated into a single offering with a common revenue mechanism. For example, if a vehicle is rented out together with a maintenance and repair contract whereby a fixed price should be paid per rental period (e.g. per day) for the total offering, this means that these elements are integrated and have a common revenue mechanism (in this case availability-based).

[2] Such a system could be implemented by equipping each radiator with a calorimeter, a tube with a special liquid that is gradually evaporated, such that the heat output of each individual radiator can be determined.

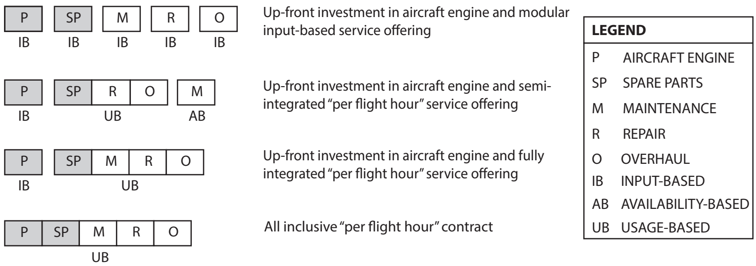

Figure 5.1: Representation of PSS options for selling aircraft engines.

Based on these characteristics (level of integration and type of revenue mechanism), a new PSS representation scheme is introduced. This scheme indicates which product and service elements are included in the PSS, how integrated they are and according to which revenue mechanisms they generate income for the provider. In the proposed graphical representation each product or service component is depicted as a rectangle, which is colored grey in case it is a product and white in case it is a service. The rectangles corresponding to different product and service components of the PSS are only connected to each other if they are integrated. Underneath the rectangle or combination of rectangles the type of revenue mechanism applicable for this element within the PSS is described (using the acronyms introduced above, e.g. PB-DO).

This representation scheme is illustrated for a manufacturer of aircraft engines in Figure 5.1. The option on the top is, according to Definition 5.1, not a PSS but a completely segregated offering of products and services, in which ownership is transferred for the product components and the service components (e.g. maintenance, repair and overhaul activities) are invoiced per intervention (e.g. with a fixed fee per activity, determined by the amount of hours and materials needed to effectuate it). The second and third option are in fact simplified descriptions of current PSSs offered by certain aircraft engine manufacturers, in which the service and spare components are combined and invoiced on a usage basis (per flying hour). The lowest option would imply a completely integrated usage-based PSS type, which would mean that the ownership of the aircraft engine is retained by the provider and an operational aircraft engine is offered per flying hour. A similar example describing theoretical PSS options for a manufacturer of optical sorting machines used for food processing (case ω), is presented in Figure 5.2.

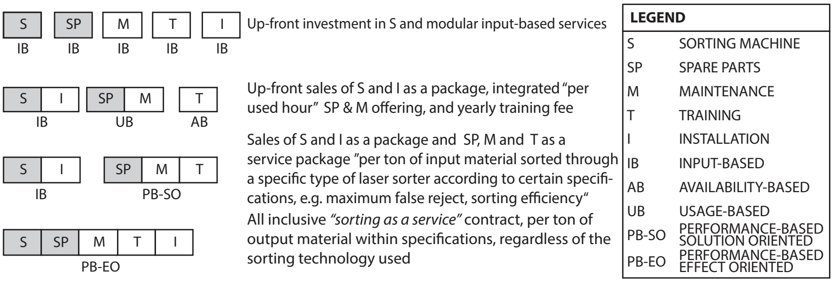

Figure 5.2: Representation of PSS options for selling sorting machines (case ω).

5.3 PSS typology

A new PSS typology is proposed based on the following distinguishing features:

- The *performance orientation of the dominant revenue mechanism* of the PSS (expressed as one of the types of Section 5.2)
- The *level of integration* of the PSS elements

The **dominant revenue mechanism** of the PSS is the revenue mechanism of the (combination of) PSS elements that represents the largest share of the life cycle revenue generated for the PSS provider from the offering. The life cycle revenue is the revenue paid to the provider calculated per unit of functional result. To determine the dominant revenue mechanism, a detailed calculation is not required; the contribution of the different PSS elements can be roughly estimated, as can be seen from the following two examples:

- Consider a company that manufactures and sells aircraft engines (with ownership transfer, thus input-based) and provides one integrated maintenance, repair and overhaul service that is charged per flight hour (usage-based). The revenue from the engine sales is divided over the total number of flight hours over the life cycle of the engine and calculated as approximately \$400 per flight hour. The revenue of the maintenance, repair and overhaul service is \$600 per flight hour. Since \$600 is a larger amount than \$400, the dominant revenue mechanism is usage-based in this example.
- Consider a manufacturer that builds and sells elevators (with ownership transfer, thus input-based) and offers a combined preventive and corrective

maintenance service charged per hour of elevator availability. If the purchase price of the elevator (e.g. €60.000) calculated over a lifetime of 20 years amounts to €3.000 per year of elevator ownership and usage and the combined maintenance service generates a revenue of €4.500 per year, than the dominant revenue mechanism is the one of the maintenance service, which is availability-based.

The level of integration, as defined in Section 5.2, indicates how many PSS elements are combined (i.e. are sold in one 'package' with a common revenue mechanism). One can roughly discern between three types: a segregated PSS, a semi-integrated PSS and a fully integrated PSS. The distinction between these types can be related to the contribution to the life cycle revenue. For example, the following rules of thumb can be applied: if more than 30% of the life cycle revenue is generated from a combined offering of PSS elements, it can be considered 'semi-integrated' and in case this is more than 80%, it is 'fully integrated'.

Based on these two distinguishing features, each PSS type can be characterized by the level of integration and the performance orientation of the dominant revenue mechanism. The naming of the types follows this convention: *integrated/semi-integrated/segregated dominant revenue mechanism type PSS*.

A particular PSS can be positioned in the grid of Figure 5.3. This grid depicts the performance orientation of the dominant revenue mechanism of the PSS on the horizontal dimension and the level of integration on the vertical dimension. Within this grid, a wide range of possible PSSs, specified according to the representation scheme presented in Section 5.2, can be positioned. The left column of Figure 5.3 corresponds to a traditional way of selling products and services, i.e. input-based, while the other columns correspond to availability-, usage- and performance based PSS types.

In Figure 5.4 five examples are presented of combinations of one product and three service elements; four extreme cases on the corner points and one example of a semi-integrated, performance based solution-oriented PSS type in the middle.

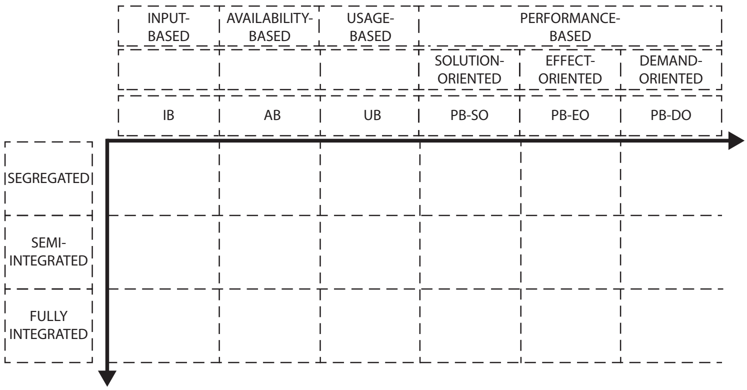

Figure 5.3: PSS types according to the level of integration and performance orientation of the dominant revenue mechanism.

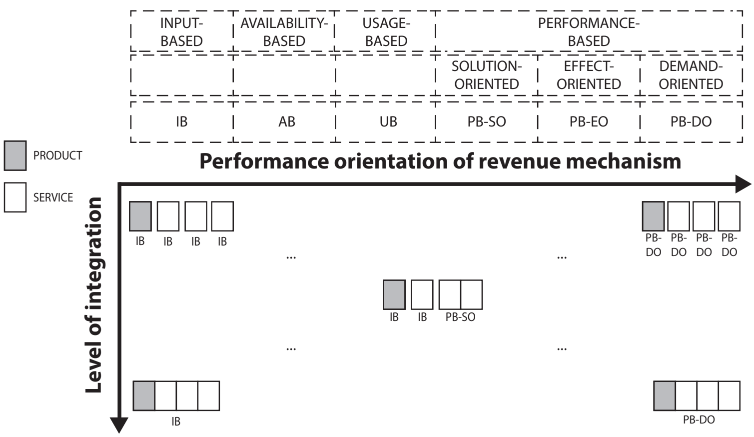

Figure 5.4: Positioning of five combinations of one product and three service elements, represented according to the PSS representation scheme of Section 5.2 in the grid of Figure 5.3.

Within the grid of figures 5.3 and 5.4, not all possible combinations are realistic for each particular case; in general a more performance oriented dominant revenue mechanism will go hand in hand with a tendency towards the integration of PSS components. The more the company providing a PSS is promising a certain level of performance, the more it will benefit from the integration of different PSS elements. The reason for this is that in a more performance-oriented PSS, the PSS provider should increase the control over the different structural elements that contribute to the fulfillment of the relevant demands or functions. If a company manufacturing radiators for example is promising a certain level of thermal comfort, it should consider the other factors that contribute to this demand fulfillment: ventilation, building insulation, etc. It might make sense to include these elements into one combined *'thermal comfort'* offering, since this gives the PSS provider more degrees of freedom to fulfill the demand in the most efficient and effective manner. Thus, a highly segregated offering with a strong performance orientation will not occur in practice.

The link between the proposed PSS typology and the FHM framework is made explicit in Figure 5.5. As can be seen in this figure, the more performance oriented the dominant revenue mechanism is, the more it is related to an element (function or demand) on a higher level of abstraction in the FHM. Solution-oriented and effect-oriented revenue mechanisms correspond to solution- and environment-centric functional expressions respectively. A demand-fulfillment oriented PSS type corresponds to a customer demand in the subjective realm. Thus, FHM aids in the systematic identification of performance-based PSS types, by specifying the different levels of abstraction. In Table 5.2 some types of PSS are presented for the examples of Table 4.1.

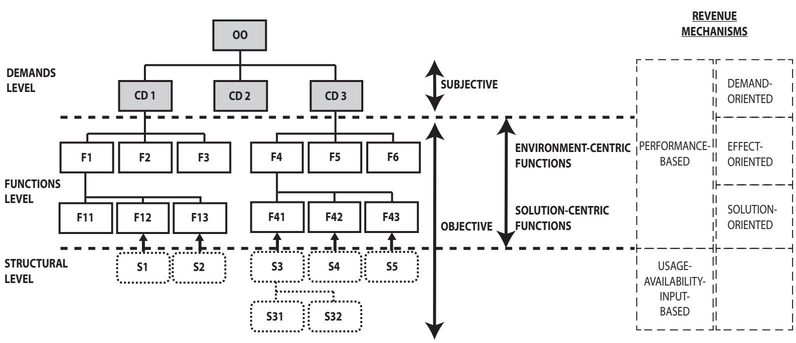

Figure 5.5: Relation of the performance orientation of revenue mechanisms and the FHM proposed in Chapter 4.

Table 5.2: Different types of PSS for the examples of Table 4.1.

Type of system	PSS example 1	Description PSS example 1	PSS example 2	Description PSS example 2
Elevator	Segregated input-based products and services	Separate sales of elevator as a product, maintenance service charged per intervention, cleaning service per day	Semi-integrated usage-based PSS	Sales of elevator as a product, integrated cleaning, maintenance and repair service charged per hour of traveling time
Space heating radiator	Integrated availability-based PSS	Sales of radiators, spare parts, cleaning and maintenance service as one package charged per day	Integrated performance based effect-oriented PSS	Integrated service whereby the air temperature in a building is kept within 20 ± 2°C, charged per month
Lighting system	Semi-integrated performance based effect-oriented PSS	Separate sales of luminaires as a product and an integrated service including lamp replacements, lighting energy consumption and lighting control system design, implementation and operation with a promised task area illuminance (expressed in lux) in a certain building	Integrated performance based demand-fulfillment oriented PSS	Integrated service of lighting system design, implementation and maintenance whereby an agreed sum is charged per day that visual comfort is offered to all building occupants.
Fire detection system	Semi-integrated availability-based PSS	Separate sales of detection system as a product, and maintenance and inspection services charged per hour of availability	Integrated performance-based solution–oriented PSS	Integrated sales of fire detection system installation, maintenance and inspection as a service charged per year that the system performs according to pre-specified functional performance indicators (e.g. specified response time, notification time,...)

5.4 Comparison of the usefulness of the refined and the classical PSS typology

As stated in Section 3.2, the value of a PSS typology primarily depends on its ability to explain the essential characteristics of the PSS concept on the one hand and on its suitability to describe a variety of PSS options within a particular industry or for a particular manufacturer (i.e. for PSS idea generation or *'PSS ideation'*) on the other hand. Both applications are briefly explored in this section.

The traditional PSS typology uses the allocation of property rights as a distinguishing feature and thus gives the impression that a use- or result-oriented PSS is not possible unless the ownership of the product remains with the PSS provider (cfr. Chapter 4). But in fact, as the example of Rolls-Royce shows, offerings with a strong usage-orientation can exist where this condition is not met. Likewise, a PSS with an orientation towards the provision of functional results does not necessarily require ownership retention by the PSS provider (e.g. PSS Example 1 for the lighting system in Table 5.2). The result of this traditional choice of distinguishing feature is that in the traditional PSS typology, use- and result-oriented PSSs are defined too strictly. This might impede the advancement of the PSS concept in practice.

In the refined PSS typology, the performance orientation of the dominant revenue mechanism is chosen as a distinguishing feature between PSS types. In our view, this characteristic, which represents the *'level of performance orientation'* of the offering, corresponds better to the central idea of the PSS concept. In the refined PSS typology, offerings can have a strong availability-, usage- or performance based logic, even if ownership remains with the customer (e.g. Example 2 for the elevator and both Examples 1 for the lighting system and the fire detection system in Table 5.2). Choosing the level of performance orientation as the main distinguishing feature for PSS types also allows to establish an explicit connection between two divergent streams of research: the PSS literature and the literature on performance(-based) contracting [88, 106].

The second application of a PSS typology, for generating ideas for PSS options, clearly benefits from a replacement of the traditional PSS typology with the more detailed typology presented in Section 5.3. The four main types of revenue mechanisms and the three subtypes within the performance-based type allow describing a larger variety of PSS options than the traditional trichotomy (see for examples the types proposed in Figures 5.1, 5.2 and Table 5.2). The important distinction between availability-oriented and usage-oriented PSS types is made in the new PSS typology (cfr. Problem 2 of Section 3.2.2), while the traditional PSS typology considers both terms as synonymous. Likewise, the fact that result-oriented PSS types can be expressed on different levels of abstraction is explicitly taken into account (cfr. Problem 3 of Section 3.2.2).

The second distinguishing feature of the refined PSS typology, the level of integration, expresses that, in a particular offering, different product and service elements can be combined to differing degrees of integration (i.e. one PSS offering can have more than one revenue mechanism). This is an important insight for the development of PSS options, since in many practical applications a completely integrated offering might not be feasible or interesting from the standpoint of the manufacturer (due to the capital requirements and risks associated with a complete integration of the offering) and/or the customer (due to, for example, lack of enthusiasm about ownerless consumption). The application of the refined PSS typology and FHM for PSS ideation, will be further explored in Chapter 6.

The main advantage of the traditional PSS typology over the refined PSS typology presented in this chapter is that the former is less complex. Typologies are devices to achieve parsimony, but a typology should not be too simple to account for the complexities in the phenomena under study. This is the case for the classical PSS typology, which creates the impression that there are only three main types of PSS to be found in practice and which is essentially flawed due to its emphasis on the allocation of ownership rights as a distinguishing feature.

5.5 FHM, the refined PSS typology and the environmental performance of PSS

This section discusses the relevancy of FHM and the refined PSS typology for the environmental goals of PSS research. As highlighted in Chapter 1, many authors view a reduction of environmental impact as an essential trait of the PSS concept. Therefore, although the assessment of ecological impact of PSSs falls out of the scope of this dissertation, we will discuss the relevancy of Chapters 4 and 5 for the environmental performance of PSS.

According to the ecological rationale, PSSs are seen as a means to achieve improved consumption and production patterns and to realize a dematerialization of the economy [15, 97, 144, 211], mainly by breaking the link between the amount of value delivered to a customer and the amount of physical materials needed to deliver that value [10]. In the context of this chapter, that link is exactly represented by the revenue mechanism(s) according to which the PSS offering is being sold to the customer. Input-based revenue mechanisms are intrinsically environmentally unsustainable, since they incentivize the provider to increase the number of inputs needed to fulfill a certain function or customer demand in order to maximize revenues. In increasing order, availability, usage- and performance-based revenue mechanisms incentivize the provider to reduce the consumption of material inputs to deliver the same function and thereby align revenue maximization with ecological impact minimization, although rebound effects should also be considered (i.e. phenomena where the absolute level of total consumption increases more than the environmental efficiency) [203]. It is expected that the highest potential for environmental impact reduction is offered by a more advanced form of PSS, i.e. one with a higher performance orientation and a higher level of integration, because the revenues of the PSS provider will be increasingly decoupled from the material and energy inputs and the PSS provider will be given more degrees of freedom respectively. The functional results type of PSS has been identified as the PSS type with the highest potential for environmental impact reduction, since it gives the provider the most possibilities to seek for more efficient alternatives to fulfill customer demands [211]. In the proposed PSS typology, the fully-integrated demand-fulfillment oriented performance-based PSS is expected to be the most sustainable PSS type.

The main contributions of the refined PSS typology and the FHM technique proposed in Chapter 4 for the environmental goals of PSS literature are twofold:

- By discerning functional results on different levels of abstraction through the application of FHM, and by accordingly differentiating between performance based solution-oriented, effect-oriented and demand fulfillment-oriented PSS types, the environmentally most promising PSS type is better understood and more easily identified. For a given system, not only one 'functional results' PSS type exists, but several performance-based PSS types can be identified on different levels of abstraction. The higher the level of abstraction on which the functional results are located, the closer the PSS approaches the concept of directly fulfilling customer demands and the more degrees of freedom the PSS provider has to deliver the functional results. Systematically generating the different innovation opportunities that are unlocked in the different performance-based PSS types can be done by using FHM as a framework and by applying the different innovation principles highlighted in Section 4.3.
- At the other side of the PSS spectrum (i.e. the upper left corner of the grid of Figure 5.3), for manufacturers that are currently working according to unsustainable input-based revenue mechanisms, the new PSS typology offers a wide range of PSS options in the transition path towards sustainable, fully-integrated, performance-based PSS types. 'Jumping'

directly from the upper left corner to the lower right corner of the grid in Figure 5.3 is in many cases not feasible from a manufacturer's viewpoint, although it is in principle most promising from an ecological perspective. Semi-integrated offerings, with revenue mechanisms that are availability-, usage- or performance-based, can in those cases be a feasible alternative for manufacturers on their way to a complete *'performance economy'* [196]. This insight can lead to a wider adoption of PSS models, and allows for the identification of more gradual transition paths towards sustainable PSS models than the abrupt transition towards use-oriented and result-oriented PSSs in the classical trichotomy.

5.6 Conclusions

As elaborated in Chapter 3, the available PSS definitions have several shortcomings and the prevailing PSS categorization into the product-oriented, use-oriented and result-oriented type fails to capture the complexity of PSS examples found in practice, because it (1) confuses a use-oriented logic of a PSS with ownership transfer, (2) does not distinguish between availability and usage, and (3) does not allow to differentiate between functional results on different levels of abstraction. This last problem is related to the fact that the notion of 'function' is not systematically treated within the available PSS literature. In this chapter a new definition, representation scheme and typology of PSSs were introduced. A PSS is defined as an integrated offering of products and services with a revenue mechanism that is based on selling availability, usage or performance. The representation scheme allows to convey the particular defining characteristics of the PSS: which product and service components are included in the offering, which of them are integrated and what are their revenue mechanisms. The resulting PSS typology is defined by the performance orientation of the dominant revenue mechanism within the PSS and the level of integration between product and service components. The different PSS revenue mechanisms introduced are related to FHM, the functional decomposition framework proposed in Chapter 4. The main theoretical contribution of the new PSS typology to the PSS field of research is that it proposes a new way of distinguishing between different types of PSS. In addition, it can be applied in practice during PSS ideation, i.e. as a framework for generating PSS options for a manufacturer of investment goods, an application which is further explored in the next chapter.

Chapter 6

PSS Ideation

PSS ideation is the process of generating PSS ideas. A PSS idea, expressed according to the representation scheme of Section 5.2, is defined by the following characteristics:

- The PSS elements (product and services) contained in the value proposition
- The revenue mechanism(s) according to which these (combinations of) PSS elements are sold
- The level of integration between these PSS elements

To generate potential PSS revenue mechanisms, the theoretical constructs of Chapters 4 and 5 can be applied directly. Specifying the level of integration of a PSS option is straightforward, by indicating which elements are to be sold in an integrated offering. Thus, the main challenge of PSS ideation lies in generating novel PSS elements.

This chapter first summarizes some relevant background on ideation in new product/service development (in Section 6.1) and subsequently provides a theoretical description of three PSS ideation support methods (in Sections 6.2, 6.3 and 6.4). Section 6.5 discusses how the PSS elements derived from applying these methods can be combined with the integration and revenue mechanism aspects of a PSS and presents some of the outputs of PSS ideation for four case studies on which the presented methods were applied.

6.1 Ideation in new product/service development

Ideation is part of the *Fuzzy Front End* of a development process [104]. In the context of New Product Development (NPD), ideation is an elaborately documented research topic. A myriad of ideation techniques has been proposed over the past decades, classifiable according to different criteria. Smith identifies 172 idea generation techniques and categorizes them based on their 'active ingredients', i.e. their strategies, tactics and enablers [190]. In addition, ideation techniques can be divided in either group methods (such as brainstorming, focus groups and the nominal group technique) or methods with individual involvement of participants. Substantial empirical evidence indicates that the latter are more effective [179]. Two main classes of idea generation techniques are distinguished by Shah [184]: intuitive techniques (that stimulate unconscious thought processes) versus logical techniques (based on systematic decomposition and analysis). Regardless of the technique chosen, the importance of involving customers or end-users during ideation is frequently asserted [113, 236].

In the context of New Service Development (NSD), ideation is seen as critical [2], but this topic has received relatively little research attention due to *"decades of neglect for service innovation"* [56]. Many companies lack structured methods, models or tools to support service ideation, although it is commonly accepted that systematic support can result in services that are better matched to customer needs and more profitable for the manufacturer [51, 72, 105]. Several authors assert that in contrast to ideation for NPD, managerial involvement during NSD ideation should be higher: the locus for ideation of successful new service offerings shifts from R&D departments to the general management level [66, 75].

The three PSS ideation support methods presented in the next sections are all analytical in nature (or, according to Shahs nomenclature 'logical') and start from a distinct theoretical framework: the Product Life Cycle (Section 6.2), the Functional Hierarchy Model (Section 6.3) and the Process Model (Section 6.4). These frameworks correspond to three different perspectives on the value creation process of the manufacturer: the first in relation to the core product, the second in relation to this product's functions and the third in relation to the processes at the customer's site in which this product is embedded.

6.2 Product life cycle ideation

For manufacturers of investment goods, in most cases a substantial share of the value for the customer is carried by a core physical product [108]. Therefore, an obvious first approach towards PSS ideation is to relate ideas for PSS elements to this core product. The reference framework that can be applied here is the *Product Life Cycle (PLC)*, a central concept within the Life Cycle Engineering stream of research.

The PLC spans the activities related to an individual product throughout its physical life, from its conception until its disposal into waste streams [103]. It can be decomposed into chronological phases, activity groups and activities. The four generic phases of the PLC are design, production, use and end-of-life (cfr. Subsection 3.3.2). Activity groups consist of all the activities performed in relation to the investment good by all actors of the value network (e.g. manufacturer, customer, certification agency). Each activity can be specified in the syntax '*do something within a context ([performed by] actor)*'. For example, within the maintenance activity group, this activity can be defined: 'replace component X after it has failed (service provider B)'. Within the proposed method, the PLC decomposition can be formulated with an appropriate level of detail, such that the identification of all relevant PSS elements is possible.

By running through the chronologically decomposed PLC, the following types of PSS elements can be identified:

- *Add-on product elements* that can be included in the company's offering (e.g. spare parts, cleaning materials, relocation kits, maintenance equipment, product manuals, software components)
- *Product-related service elements* that can be included in the company's offering (e.g. operator training, audit and consulting services, insurance, risk assessments, purchase and sales options of second hand machines). The development of product-related services is identified by Oliva and Kallenberg as the first step on the transition trajectory from product manufacturer to service provider [154].
- *Combinations of add-on product and product-related service elements* that can be included in the company's offering (e.g. a condition monitoring system that sends automatic status updates to users and that can trigger a remote troubleshooting service, a maintenance service that includes the supply of spare parts, an upgrading service containing component replacements and operator training)

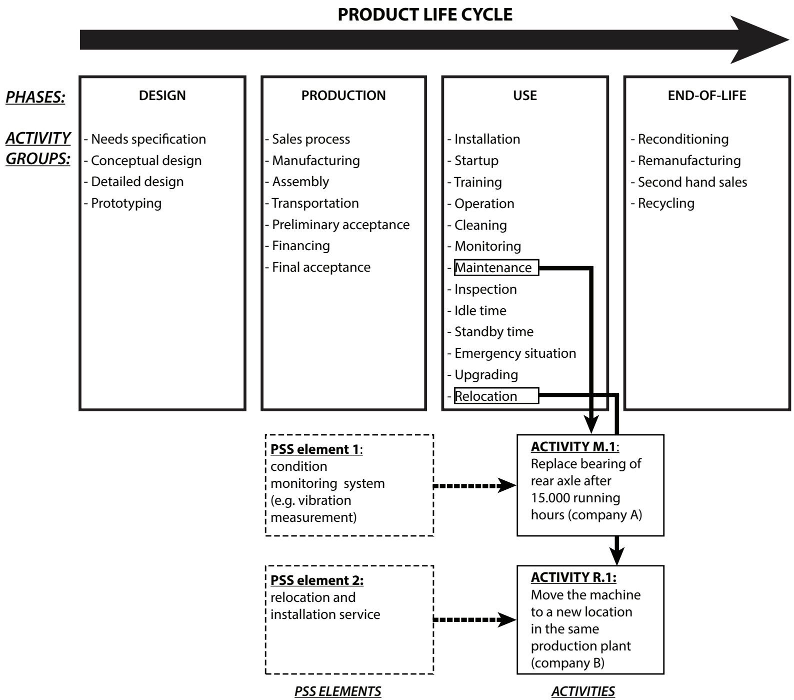

Figure 6.1: Working principle of the PLC ideation method.

A generic overview of the Product Life Cycle of an investment good is presented in Figure 6.1. This figure contains a schematic representation of the working principle of the first PSS ideation support method.

In Table 6.1, a non-comprehensive, generic list is presented of add-on product elements, product-related service elements and combinations of both, according to the activity groups of the PLC of an investment good. In the last column, the names of various industrial manufacturers are added that currently offer the corresponding PSS elements. These were derived from an analysis of these companies' online product and service catalogues.

Table 6.1: Generic PSS elements derived through PLC ideation, with industrial examples.

Activity	Generic PSS Element	Industrial examples
	1. DESIGN PHASE	
Need specification	Audit and consulting services	ABB, SKF, Kalmar Terminal Development
	Web based need specification tool	Kone Elevators Traffic Analysis
Conceptual design	Offering of drawings and 3D models to users	Kone Elevators
Detailed design	Offering of engineering skills to external parties	SKF Energy efficiency, Alloyd Brands Packaging design, Liebherr Electronic Engineering
	Customized design service	Seco
Prototyping	Prototyping service	Alloyd Brands Package prototyping
	2. PRODUCTION PHASE	
Production	Offering of production or logistical processes to external customers	Logistics (Caterpillar, SKF) Castings production (Picanol, Caterpillar)
Transportation	Differentiated transportation service (e.g. with tracking)	Metso
Acceptance	(Preliminary) acceptance service	Zwick, Kapp
Financing	Alternative financing options (leasing/renting)	Xerox, Arcomet, CMI Locomotives
	3. USE PHASE	
Installation	Integrated with removal service of obsolete product	Kone Elevators
Production Start	Startup service: support production ramp up	Kuka Robotics
	Trial use of a product (e.g. temporary rental)	BEST Sorting
Training	Predefined training packages	ABB, Atlas Copco, Caterpillar
	Online training portal	Atlas Copco, Trumpf
Operation	Consumables and accessories	Trumpf, Kohler Power, Grundfos
	Direct materials	Apex Packing Corporation
	Integrate advertising in product	Selecta vending machines,
Cleaning	Cleaning service or cleaning products	Alfa Laval
Monitoring	Monitoring and visualization service	Claas Remote Diagnostics
	Periodical system status reports	Schindler, Philips Healthcare

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Table 6.1 (Continued): Generic PSS elements derived through PLC ideation, with industrial examples.

Activity	Generic PSS Element	Industrial examples
Maintenance	Maintenance service for equipment of competitors at customer's site	Schindler, Demag Cranes
	Inspection service	GE Energy
	Condition monitoring systems for critical components to streamline diagnosis and repair actions	Atlas Copco
	Differentiated service levels (reaction times, spare parts availability, backup unit provision)	Siemens Building Management
	Backup unit during breakdown	CMI, Case New Holland
	Remote support service or remote inspection	Zwick, EMAG
Inspection	Periodical inspection service	Demag Cranes
Emergency situation	Periodic risk assessments	Rockwell Automation
	Theft protection system and/or insurance	Atlas Copco, John Deere
	Insurances combined with the product	Vestas, John Deere Crop Insurance, Kubota
Upgrading	Upgrading service that allows customer to outsource the risk of technological obsolescence	Rockwell Collins Obsolescence Services
Relocation	Machine relocation service	Zwick, KBA, ASML, Metso
	4. END-OF-LIFE PHASE	
Reconditioning	Reconditioning service to increase lifetime	ABB, GE Energy
Remanufacturing	Refurbished parts offered as spares for aging equipment	GE Energy, Bobcat
Second hand sales	Second hand trading (own products and/or other brands)	Caterpillar, Jungheinrich, Trumpf
Recycling	Take back and recycling service of old products	Kennametal Carbide Recycling, Daikin

6.3 Functional hierarchy model ideation

In Functional hierarchy model ideation, ideas for PSS elements are generated by analyzing the FHM that ties the investment good to its overall objective for certain customer segments. This FHM is constructed according to the guideline of Section 4.2. By runnning through all levels of the hierarchy, the following types of PSS elements can be identified:

- *Functional optimization services* assist the customer in attaining or improving performance on the functional level of the hierarchy. These are consulting and/or design services whereby the customer is supported in optimizing a combination of structural elements in the FHM towards the realization of a common function. For example, a manufacturer of lighting systems can offer a service in which the customer is advised on how to achieve an appropriate illuminance of all task areas, not confined to lighting systems, but including changes to construction elements (windows, reflective walls, light domes) that influence the attainment of this function[1].

- *Demand optimization services* are similar to the previous category and support the customer in achieving an optimized fulfillment of one or multiple demands. A manufacturer of lighting systems could offer advise on how to optimize the visual comfort inside a building, whereby all functions contributing to this demand are taken into account (e.g. visual glare and color rendering). Alternatively, he could consider supporting the customer in the optimization of multiple demands at the same time, e.g. visual comfort and acoustic performance.

- *Functionally related PSS elements* are products or services that the company can add to its offering. All structural elements on the lowest level of the hierarchy might qualify. Their inclusion only makes sense if this entails potential strategic benefits for the manufacturer. They might for example allow to capture value from a wider deployment of the company's strategic resources. A provider of fire detection systems whose strategic resources include application knowledge, project management skills and customer relations, could benefit from offering building security systems (e.g. security cameras) besides its traditional fire safety systems. A company that sells and services manual fire extinguishers could put its efficient distribution channel to a wider use by offering components for signalisation and emergency lighting as well.

[1]Cfr. the FHM of a lighting system, Figure A.4 on page 233.

- *Hybrid offerings with external partners* are combinations of structural elements offered by two or more companies. These structural elements are related to the same function, the same demand or even to different demands. An example of a hybrid offering related to the same function, is a combination of a lighting control system and a set of light domes. An example of a hybrid offering related to the same demand is a combined fire insurance service and fire safety system. An example of a hybrid offering related to different demands is an integrated ceiling system with LED lighting and acoustic panels, that attains both visual comfort and acoustic performance in office buildings. Philips Lighting and Ecophon, a global supplier of acoustic systems, claim to have developed such a system under the name *SoundLight Comfort Ceiling* [117]. External partners suitable for co-creating hybrid offerings can be seen as potential *complementors* [77].
- *Functional substitutes* are PSS elements that allow to provide functional results or fulfill demands more efficiently than the structural elements that are currently in use. Functional substitutes can be related to the four types of innovations in the FHM presented in Section 4.3 (cfr. page 64). Examples are a centralized voicemail service that substitutes a physical answering machine, a video conferencing system that replaces the need for business travel planning and transportation services and a passive solar building design that (partially) substitues a central heating system. Functional substitutes entail the largest potential for radical innovation, as they can alter the FHM thoroughly by changing the way that functions are provided or demands are filfilled.

6.4 Process model ideation

Every investment good can be represented as a part of the customer's processes. According to standard EIA/IS 632, a process is any set of interrelated tasks that, together, transform inputs into outputs [128]. A discrete manufacturing machine, for example, has raw materials, intermediate goods, energy, etc. as inputs and finished parts as outputs. Elevators consume various resources (e.g. energy, materials, service technician hours) to deliver a vertical transportation service. The focus of Process Model (PM) Ideation lies in analyzing the investment good's role from a process perspective. PSS elements are identified that are related to the activities happening before and after the investment good does its own set of tasks.

A wide variety of process modeling techniques and tools are described in various streams of research [87, 137]. For Busines Process Modeling (BPM), a topic in

Information Systems, a lot of academic and commercial work has been published over the last decades [92, 167]. A popular modeling technique within BPM is Event-driven Process Chains (EPCs) [49, 136]. EPC uses a simple syntax of *activity types* (process steps), *event types* (pre-conditions and post-conditions of process steps) and logical connectors (AND, OR, XOR, ...). A process model structure should be intuitive to understand and it should have a low error probability [137].

By following the EPC syntax, a process model was derived for a diamond polishing system as an example. A diamond polishing system can polish diamonds automatically, as opposed to the current polishing method in the diamond gemstone industry, which is manual and mostly performed in countries with low labor costs. In order to gain insight in the process chain in which a diamond polishing system would be embedded, three potential customers for this type of machine were interviewed – all senior representatives of diamond processing companies in Antwerp. Their information is combined in the process model of Figure 6.2.

As can be seen from this figure, the process chain is geographically dispersed, with two routes for sawing and three for bruting and polishing. Remarkable are the intermediary inspection as well as the final grading step in Belgium. During the interviews with the representatives of the diamond processing companies, quantitative information was gathered on each step of the process of Figure 6.2 in order to be able to quantify the additional value of automatic diamond polishing in comparison to the current way of working, taking into account the cost of the manual and automatic processes as well as the additional value of the automatic over the manual process (e.g. reduced leadtime and risk of damaging the stone). This is further developed in Chapter 8.

But here, the focus is on identifying PSS elements through PM Ideation. Regardless of the process modeling syntax used, after the process model is constructed, the following PSS element types can be identified along this dimension:

- In analogy to demand or functional optimization services, *process optimization services* are consulting and/or design services whereby the customer is supported in the optimization of (part of) his processes. In the example of a diamond polishing system, the provider might offer process optimization advise for the complete chain of Figure 6.2.
- *Process related PSS elements* are products or services that correspond to certain activities in the process model and that can be added to the company's offering. Although in general they are not necessarily related to the same functions or demands as the investment good, the manufacturer

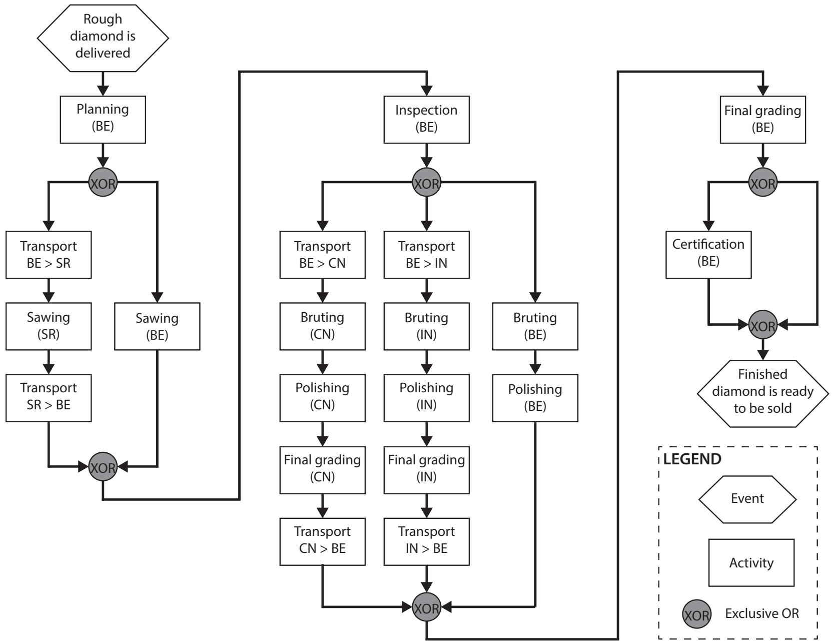

Figure 6.2: Process model for a diamond polishing system. For each activity, its location is indicated (BE = Belgium, CN = China, IN = India, SR = Sri Lanka).

might see strategic advantages in adding them. For example, if a provider of a diamond polishing system offers a maintenance and repair service for sawing and bruting equipment, this might add convenience for the customer and generate additional revenue for the provider.

- As in FHM ideation, *hybrid offerings with external partners* are possible too if there is a process relation between systems. For example, the provider of diamond polishing systems and a specialized diamond transportation company might set up a pick-up, polishing and drop-off service whereby the diamonds are gathered at the customer's site and brought back after polishing.

- Finally, *process substitutes* are novel PSS elements that allow to replace (part of) the customer's processes. For example, if an automatic system would be developed that saws, brutes and polishes diamonds in one automatic setup, it could substitute part of the process chain of Figure 6.2.

6.5 Output of PSS ideation

By applying one or more of the ideation methods of the previous sections, a varied set of PSS elements can be derived. These PSS elements can be combined with the PSS elements that the company is already offering, by indicating the following characteristics:

- the revenue mechanisms: all options can be determined by drawing the teleological chain as explained in Section 4.2.3 and by applying the typology of revenue mechanisms of Section 5.2
- the level of integration: this can be determined with guidance of Section 5.2

In Table 6.3 a sample of PSS options is presented that were formulated within various case studies of the research project BOSS. The companies for which these PSS options apply, are introduced in Chapter 2. As can be seen from this table, most PSS options are derived through PLC ideation, which is logical, given the facts that the majority of these companies currently has a product-centric business model and that the introduction of product-related services is the first step on the servitization transition trajectory of a product manufacturer [72, 154]. A visual representation of the PSS options of Table 6.3 according to the representation scheme introduced in Section 5.2 is provided in Figure 6.3.

Table 6.2: Legend of all PSS elements of Figure 6.3

AD	Adaptations	**FDS**	Fire Detection System	**OSM**	Optical Sorting Machine
BR	Bruting Equipment	**FG**	Final Grading	**PI**	Process Integration
C	Cleaning	**FSE**	Fire Safety Engineering	**PL**	Planning Equipment
CB	Conveyor Belt	**IM**	Implementation	**PO**	Process Optimization
CP	Control Panels	**IO**	Illuminance Optimization	**POL**	Polishing Equipment
D	Detectors	**IS**	Inspection	**R**	Renovation
D*	Detectors (extra 5-10%)	**ISR**	Insurance (fire)	**SP**	Spare Parts
DI	Demand Integration	**L(C)S**	Lighting (Control) System	**SW**	Sawing Equipment
DR	Detector Replacements	**LSM**	Low-end Sorting Machine	**T**	Telephony
DS	Drive System	**MA**	Maintenance	**TR**	Transport
E	Elevator	**MO**	Monitoring	**VG**	Ventilation Grid Control System
EN	Energy	**MP**	Materials Purchase	**WS**	Weighing System
ENI	Energy Improvement	**OP**	Operation	**LR**	Lamp Replacements

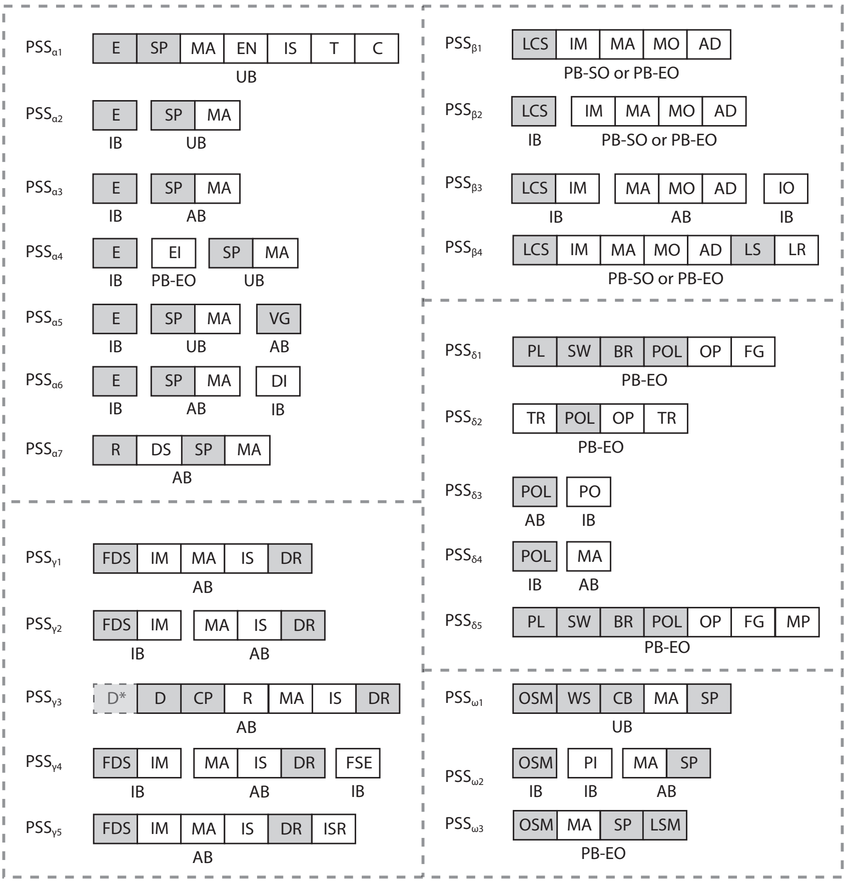

Figure 6.3: PSS options for traction elevators (α), lighting control systems (β), fire detection systems (γ), diamond polishing systems (δ) and optical sorting machines (ω). A legend of the abbreviations of the PSS elements is provided in Table 6.2 and a detailed description of these PSS options is provided in Table 6.3.

Table 6.3: PSS options for traction elevators (α) and lighting control systems (β).

PSS option	Description	Ideation method
$PSS_{\alpha 1}$	Sales of all inclusive elevator service (including investment, maintenance, spare parts, energy, periodic inspection, telephony, cleaning) in an integrated offering per travel cycle (usage based (UB) revenue mechanism).	PLC
$PSS_{\alpha 2}$	Sales of elevator as a product (IB) and of a separate maintenance and spare parts service charged per travel cycle (UB).	PLC
$PSS_{\alpha 3}$	Sales of elevator as a product (IB) and, separately, of a maintenance service including spare parts, charged per month of elevator availability (AB).	PLC
$PSS_{\alpha 4}$	Sales of elevator as a product (IB) and, separately, of an energy improvement service whereby the savings in energy cost (in €) is shared between company α and the customer (PB-EO). Separately, a maintenance service and spare parts package are sold per travel cycle (UB).	PLC
$PSS_{\alpha 5}$	$PSS_{\alpha 2}$ + leasing of a control system of the ventilation grid in the elevator shaft (AB)	PM
$PSS_{\alpha 6}$	$PSS_{\alpha 3}$ + demand integration service, consulting the customer on how to achieve an optimized flow of people in a building, charged per hour of consulting (IB).	FHM
$PSS_{\alpha 7}$	Sales of an integrated elevator renovation, drive system replacement and maintenance/spare parts service, specifically for customers with an outdated, energy inefficient Ward Leonard drive system, charged at a fixed yearly rate (AB).	PLC
$PSS_{\beta 1}$	Sales of a lighting control system (LCS) and life cycle support services (maintenance, monitoring, adaptations) in an integrated offering whereby the lighting energy consumption after implementation is monitored, compared to the base case consumption and the cost savings (in €) are distributed between company β and the customer (PB-EO). Alternatively, β is paid with a fixed compensation per kWh saved (PB-SO). In this option, the wiring installation cost is excluded (i.e. should be paid separately by the customer to the electrical installation company).	PLC
$PSS_{\beta 2}$	Sales of LCS materials as a product (IB) and of the (labor-related) implementation and life cycle support services paid according to a PB-EO (per € saved) or PB-SO (per kWh saved) revenue mechanism.	PLC
$PSS_{\beta 3}$	Sales of LCS materials and implementation service at a certain distance-independent price per node (IB), life cycle support services at a fixed monthly rate (AB) and functional integration service charged per hour of consulting (IB) whereby the customer is advised on how to optimize his building and lighting systems to attain the required illuminance (in lux) at the lowest cost.	FHM
$PSS_{\beta 4}$	Fully integrated lighting and lighting control system, sold according to a PB-EO (per € saved) or PB-SO (per kWh saved) revenue mechanism	FHM

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Table 6.3: PSS options for fire detection systems (γ), diamond polishing systems (δ) and optical sorting machines (ω).

PSS option	**Description**	**Ideation method**
$PSS_{\gamma 1}$	Sales of a fire detection system (FDS), integrated with implementation and life cycle services (maintenance, inspection, replacements), charged at a fixed yearly payment per node (AB).	PLC
$PSS_{\gamma 2}$	Sales of an FDS as a product and installation service per resources consumed (IB). Separately, life cycle services are offered at a yearly rate per node (AB).	PLC
$PSS_{\gamma 3}$	Integrated offering consisting of the renovation of an existing FDS over a period of five years (i.e. replacement of all detectors and control panels) and all life cycle services during a period of fifteen years, starting from the first year of renovation, charged at a predetermined yearly rate per node (AB). Two sub-options were considered within this model: one where the number of detectors remains constant and one where the number of detectors is increased with 5-10% during renovation.	PLC
$PSS_{\gamma 4}$	$PSS_{\gamma 2}$ + fire safety engineering service, a demand optimization service consisting of advise during the construction design phase to optimize the first safety of people, property and buildings, charged per hour of consulting (IB).	FHM
$PSS_{\gamma 5}$	Hybrid offering of an FDS, life cycle services and an integrated insurance service at a yearly rate per node (AB).	FHM
$PSS_{\delta 1}$	Completely integrated *diamond processing service* charged *per carat polished* (PB-EO), including planning, sawing, bruting, polishing and final grading.	PM
$PSS_{\delta 2}$	Automatic polishing service charged per carat polished (PB-EO) including pick-up and delivery.	PM
$PSS_{\delta 3}$	Leasing of diamond polishing system (AB), plus a process optimization service charged per hour of consulting (IB).	PM
$PSS_{\delta 4}$	Sales of diamond polishing system with property transfer (IB) and maintenance services at a yearly payment (AB).	PLC
$PSS_{\delta 5}$	PSS option $PSS_{\delta 1}$ integrated with purchasing of rough material. In this model, company δ is acting itself as a diamond processing company and selling finished gemstones (PB-DO).	PM
$PSS_{\omega 1}$	Sales of a sorting machine, with process add-ons (weighing system, conveyor belt) and maintenance and spare parts, per used hour (UB).	PM
$PSS_{\omega 2}$	Sorting machine sold as a product and separately a process integration service whereby other equipment in the customer's production process (machines for cutting, washing, packaging) are thoroughly scanned to improve the total process performance (yield, false reject,...), paid per hour of consulting (IB) + maintenance and spare parts sold at a fixed monthly rate (AB).	PM
$PSS_{\omega 3}$	Adding low end sorting machines to the product offering (e.g. to remove large stones in fruits) and selling them in an integrated offering with optical sorting machines, maintenance and spare parts, per ton output material (PB-EO).	FHM

6.6 Conclusions

This chapter discussed how PSS ideas can be generated systematically. After explaining some background on ideation in NPD and NSD, three PSS ideation support methods for manufacturers of investment goods were presented. Each of these methods is applicable for supporting the process of generating new PSS elements. By specifying revenue mechanisms and the level of integration according to the representation scheme of Chapter 5, these novel PSS elements can be combined with the products and services the company is already offering in a varied set of PSS options. The three PSS ideation support methods offer a complementary view on the way the investment good provides value for the customer:

- For manufacturers at the start of the transition trajectory from product manufacturer to service provider, PLC ideation allows to identify product-related service elements, add-on product elements or combinations of both along the chronological perspective of the investment good's life cycle.
- Further on the transition trajectory, one possible evolution path is that the company adds PSS elements that contribute to related functions or demands in its FHM. Thus, the following types of PSS elements can be identified; functional optimization services, demand optimization services, functionally related PSS elements, hybrid offerings with external partners and functional substitutes. Here, the teleological perspective of the investment good's functional hierarchy is the essential ideation perspective.
- Alternatively or additionally, a company could add elements to its product and service portfolio by looking at PSS elements that play a role in the customer's processes. PM Ideation allows to identify the following types of PSS elements: process optimization services, process related PSS elements, hybrid offerings with external partners or process substitutes. Ideation is performed here according to the activity chain perspective offered by process models.

Given the scarcity of available systematic support for the ideation phase of PSS development, the three techniques introduced within this chapter enhance the state of the art, by looking at the value creation process of the manufacturer in three different dimensions; the life cycle of the product, the functional hierarchy and the customer processes. Now that a varied set of PSS options is derived, the manufacturer needs to be supported in analyzing the business potential of each PSS option. This is the subject of Chapters 7 and 8.

Chapter 7

Quantifying the business potential of a PSS: Methodology

In this chapter, a novel methodology is presented to assess and analyze the business potential of a particular set of PSS options (such as the ones determined in Chapter 6) for a manufacturer of investment goods. This methodology is composed of four steps (cfr. Figure 7.1):

1. *Goal and scope definition*: First, the objective and limitations of the economic evaluation are determined, such as the customer segments and technical systems under consideration and the cost and value components that will be included in the analysis.

2. *Model development*: Subsequently, a model is developed that allows to generate estimates for the cost and value per functional result of the investment good. The structure of input parameters, output parameters and the relations that link outputs to inputs are determined.

3. *Data gathering, output analysis and validation*: The third step of the methodology entails gathering data, modeling uncertainties and risks, running simulations, analyzing model outputs and validating the model in an iterative loop until a desired level of accuracy is achieved.

4. *Improvement scenario analysis*: When the model is validated, a set of improvement scenarios is determined, each of which describes a specific,

realistic and quantifiable idea on how cost can be reduced or how value can be increased per functional result. Then, these scenarios are linked to the PSS options that were determined during PSS ideation, by indicating which improvement scenario can be 'realized' by which PSS option. i.e. in which PSS option the provider will benefit financially from the realization of the corresponding improvement scenario. Thus the cost reduction and value improvement potential of each PSS option is determined.

Each of these steps is discussed in detail in Sections 7.2, 7.3, 7.4 and 7.5. But first, in Section 7.1, the proposed methodology is described according to the nine criteria that were used in Section 3.4.2 to characterize existing methods, theories and tools for the economic evaluation of PSS.

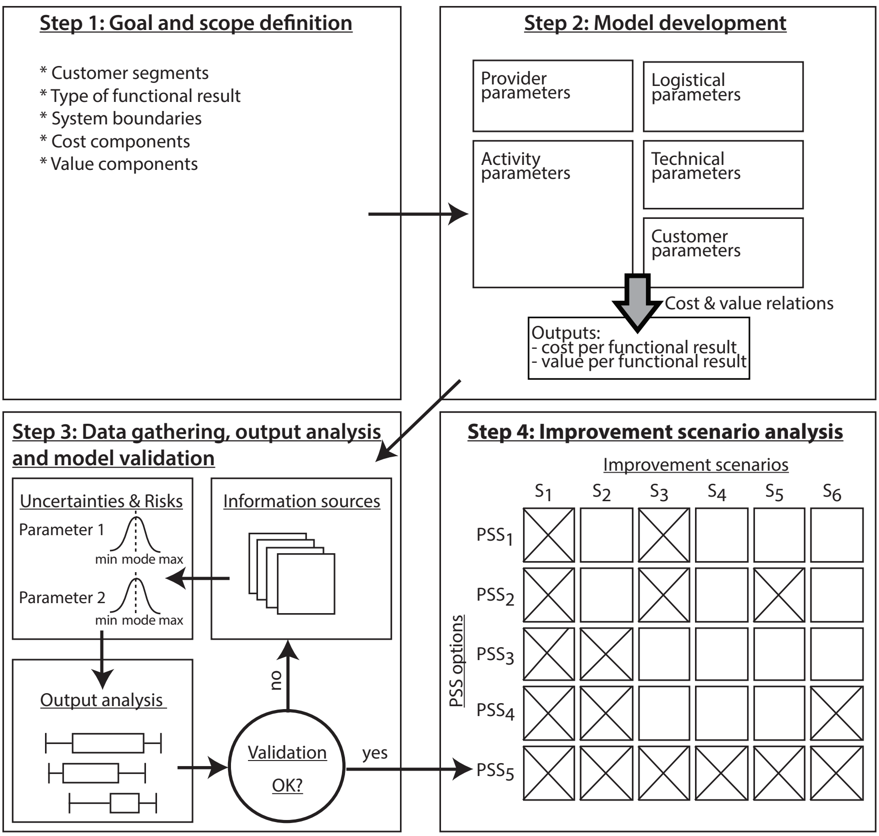

Figure 7.1: Schematic overview of the proposed methodology.

7.1 Characterization and novelty of the proposed methodology

According to the criteria of Section 3.4.2, the proposed methodology can be characterized as follows:

- The methodology has a *combined perspective*: on the one hand cost is evaluated from the PSS provider perspective, on the other hand value is looked at from the customer perspective.
- Predominantly *quantitative evaluation criteria* are taken into account. Cost is quantified in monetary terms, while for value, both monetary and non-monetary criteria are used.
- This methodology is applicable during the *phases* 'analysis of PSS opportunities', 'PSS idea generation' and 'PSS design', since it is especially intended to support ex ante evaluation of the economic attractiveness of a PSS model and to guide design teams in focusing on design parameters with a high impact on cost or value. The desired level of accuracy that is to be reached in the third step – *data gathering, output analysis and validation* – will be determined by the phase in which the evaluation takes place. If the methodology is solely applied for the analysis of PSS opportunities, only a rough approximation of the cost and value is required, while in the PSS design phase more reliable estimates should be derived. Thus, the level of accuracy is determined ad hoc and in consultation with the company for which the analysis is performed.
- The methodology allows to take relevant *uncertainties and risks* into consideration through a combination of Monte Carlo simulation and scenario analysis.
- The primary purpose of this methodology is to quantify the *PSS innovation potential*.
- The economic benefits of a PSS are primarily sought in the *mechanisms* 'cost reduction' (*Mechanism 1*) and 'value increase' (*Mechanism 2*). The rationale behind this choice is that they are essential for estimating the PSS innovation potential (cfr. Section 3.4.1), the specific focus of this methodology. Predicting the other mechanisms, i.e. how the customer base could grow with the introduction of a PSS and how the competitive environment could be affected, requires the modeling of complex market dynamics and the determination of actual WTP (corresponding to price) instead of maximum WTP (corresponding to value). To quantify the actual

WTP of customers, techniques could be incorporated from pricing research, such as conjoint analysis, discrete choice analysis, price estimation scene, etc. [29]. But the majority of these techniques are based on extensive, time-consuming surveys, given the fact that customer preferences can be variable, even within one customer segment, and that they can change over time. Moreover, aspects such as customer loyalty and switching behavior should be accounted for. To avoid these difficulties, the choice is made not to estimate actual WTP but to focus on maximum WTP, value, which can be quantified in a more time efficient way for investment goods, as will be discussed in Section 7.2.

- The *basis of evaluation* chosen is one functional result. In other words, the evaluation aims to answer this question: 'How much value can be added and how much cost can be reduced per functional result in a PSS model?' The reason for this important choice is that the *business potential of an integrated performance based PSS type is the theoretical maximum potential of any PSS type* if only the mechanisms 'reduce cost' and 'increase value' are taken into consideration. As elaborated in Section 5.5, a provider has the most degrees of freedom to design an optimal solution for a certain customer demand in the performance-based type of PSS.

The *novelty* of the presented methodology mainly lies in the following aspects:

- If compared to the approaches listed in Section 3.4.2, this methodology is the only one that allows for an evaluation of the PSS innovation potential in both cost and value, by combining the perspective of the PSS provider and the customer.
- The presented methodology includes a novel generic approach for quantifying the value-in-use of an investment good, both in monetary and non-monetary terms. A generic decomposition of value components is proposed, as well as four value quantification strategies that can be applied for this purpose (cfr. Section 7.3.1).
- The presented methodology is well-equipped to deal with uncertainties and risks that are relevant for the evaluation, through a combination of Monte Carlo simulation and scenario analysis.
- As indicated in Section 3.4.2, a major limitation of most PSS evaluation approaches is their limited proven transferability on multiple case studies. In Chapter 8 five in-depth case studies are elaborated that allow to validate the methodology presented in this chapter.

7.2 Step 1: Goal and scope definition

The first step requires defining the goal and scope of the evaluation, which includes the customer segments, the basis of evaluation, the system boundaries, the relevant cost and value components.

7.2.1 Customer segments

First, a decision should be made whether the scope of the evaluation will be limited to particular groups of (potential) customers with similar demands. This can be necessary because some investment goods are applied in fundamentally different contexts, and trying to include all customer segments into a single model can needlessly complicate the set of parameters and the corresponding uncertainties. Moreover, the functional result(s) of an investment good can be fundamentally different for different customer segments. For example, an optical sorting machine can be used for sorting contaminants out of food or for sorting valuable PCBs out of e-waste. Both types of customers require a fundamentally different type of functional performance (e.g. food safety versus maximization of recovered value) and would require different input parameters (e.g. percentage of food items with discolorations versus applied shredder size). Therefore, trying to aggregate them into a single model is not advisable.

Performing customer segmentation, a central method of marketing research for more than 50 years [70, 192], requires the selection of a segmentation basis; the criterion that allows to discern homogenous groups within the potential customer base. Preferably, this segmentation basis is related to functional characteristics of the investment good, but other differentiation criteria could include the usage intensity or distribution channel. Subsequently, the segments that are deemed more suitable for a PSS model should be selected. The following criteria can indicate for which segment(s) a PSS is a better option (partially based on the conditions mentioned in [202, 212]):

- **Material, labor and energy intensity.** For customers that use products more intensively, a PSS would normally be more interesting, because theoretically a larger cost reduction potential could be achieved.
- **Core competences.** In general, a PSS that shifts responsibilities towards the provider, will be interesting for customers if they do not regard the operation or maintenance of this investment good as a strategic ‘core competence’.

- **Consequences of malfunction.** In general, a PSS is more interesting if the consequences of malfunction of an investment good are more important, because (theoretically) the provider will be able to offer a larger value improvement.
- **Market/customer size.** Implementing a PSS often requires investments in service capabilities and infrastructure. These investments can only be recuperated if a large enough customer base can be catered to. Therefore larger customer segments with larger individual customer firms are in principle more interesting.

Performing this initial, qualitative evaluation cannot be automated, but requires the strategic insights of company representatives or industry specialists that understand the customers within the relevant markets.

7.2.2 Basis of evaluation

The basis for the economic evaluation is one functional result, which is defined according to Definition 4.2 as a standardized unit of function delivery. As we have seen in Chapter 4, functional results can be expressed on different levels of abstraction, corresponding to the levels within the Functional Hierarchy Model of the investment good. Examples of functional results that can be chosen as a basis for evaluation are presented in Table 4.1 on page 61.

The business potential of a PSS will strongly depend on which functional result is chosen as an evaluation basis. If, for the example of a space heating radiator, the solution-centric functional result is chosen, the fact that space-heating radiators are selected as a specific solution limits the scope of the analysis and the degrees of freedom for optimization are restricted to aspects such as the radiator design, its location within the building and the maintenance and cleaning service. If the environment-centric functional result is chosen, the total system of maintaining a room temperature within the specified bounds is considered, including heat generation, building insulation, etc. The potential cost or value improvements in those factors will be reflected in the business potential of a PSS. If the demand-fulfillment result is chosen, the scope is even wider: other solutions to achieve the same comfort level (e.g. adjustments of air flow or humidity) will also be within the scope of the analysis. Thus, the choice of the evaluation basis will severely influence the scope of the evaluation: it determines which degrees of freedom will be included.

7.2.3 System boundaries

Next, the system boundaries should be stated explicitly. They are related to the time horizon (e.g. '10 years'), the geographical location (e.g. 'customers located within 100 km of the provider's headquarters') and the technical environment (e.g. with or without peripheral equipment). The system boundaries will determine what is considered to be a cost reduction and what a value improvement: if a system B is not within the system boundaries, cost savings that can be realized in B are considered to be value improvements rather than cost reductions.

For a large part, the system boundaries will be influenced by the choice of evaluation basis. If, for the example of a radiator, the demand-fulfillment result is chosen, the system boundaries cannot be restricted to radiators alone, but should include other factors as well (i.e. the factors that are connected to thermal comfort in the radiator's FHM[1], such as ventilation systems and building insulation). Each of the assumptions and simplifications made during this stage should be justifiable, but will be determined largely on a subjective basis.

7.2.4 Cost components

All cost components that will be included in the analysis are to be determined. Costs refer to all resources that are consumed by the system (which is delineated as in Subsection 7.2.3) to deliver one functional result (which is chosen as a basis of evaluation as in 7.2.4). All cost components can be organized in a Cost Breakdown Structure as explained in Section 3.3.2, decomposed according to the generic phases and activity groups of Figure 6.1 on page 86.

7.2.5 Value components

Similarly, for the value assessment, the relevant value components should be identified. While cost components are organized chronologically, value components can be organized according to aspect types. Several typologies and classifications of value aspects have been proposed [115]. Based on existing work [40, 115, 159], a generic typology of value aspects for investment goods has been derived and is presented in Table 7.1. Besides the main aspects of customer value related to ownership or usage of an investment good, it includes

[1]Cfr. Figure 4.5 on page 63.

some underlying value components and examples of performance indicators that can be chosen to reflect the corresponding components.

Table 7.1: Typology of value aspects, with an example decomposition into value components and related performance indicators

Value aspects	**Value components**	**Examples of performance indicators [units]**
Assurance	Competence of provider personnel	Evaluation of service experience [subjective scale]
	Conformity to norms and standards	Conformity to specific standard [binary]
Convenience	Ease of operation	Evaluation of service experience [subjective scale], Number of operating failures per month [Number]
	Ease of maintenance	Diagnosis time [hours]
	Ease of information retrieval	Time to obtain a particular piece of information [minutes]
Responsiveness	Responsiveness to emergencies	Response time$_1$ [minutes]
	Responsiveness to regular service requests	Response time$_2$ [hours]
Safety	Impact on risks of work accidents	Number of incidents per year [nr] Impact of occurrence[severity metric]
	Impact on fire safety risks	Number of incidents per year [nr] Impact of occurrence[severity metric]
Flexibility	Multi-functionality	Potential savings or extra revenues due to extra functions [€]
	Ability to cope with changing customer demands	Time to change setup to other product type [hours]
	Ability to facilitate external cost savings	Potential external cost savings [€]
Productivity	Reliability	Mean time to failure [hours]
	Maintainability	Mean time to repair [hours]
	Capacity	Throughput [Units per hour]
	Accuracy	Total depreciation of end products due to inaccurate processing [€]

As can be seen in the third column of Table 7.1, most of these performance indicators are expressed in non-monetary units (e.g. time units, number of occurrences, subjective score).

At this point, the scope and objectives of the assessment have been determined. Now, the model can be assembled that will be used to estimate the cost and value potential of a PSS.

7.3 Step 2: Model development

At the core of the proposed methodology lies a Monte Carlo simulation model that enables a stochastic assessment of the cost and value per functional result of the investment good, and that is combined with scenario analysis to evaluate the innovation potential of a PSS. The implementation can be done in a spreadsheet environment, using statistical software add-ins (cfr. Subsection 3.3.2). This section describes the generic structure of the simulation model: its main logic, the type of input parameters included, the type of outputs, as well as the parametric relations that reflect how outputs are deduced from inputs.

7.3.1 Main logic and output parameters

The model has two types of outputs: those that reflect the *cost* and those that reflect the *value* per functional result of the investment good. The cost per functional result is presented from the point of view of the provider. Value is assessed from the customer's perspective. In this section, we will describe according to which logic both types of outputs are calculated.

Cost outputs are calculated by applying stochastic LCC in combination with TD–ABC (cfr. Section 3.3). All activities over the lifetime of the investment good that contribute to the realization of a functional result are defined and the cost of each activity is derived by calculating which resources it consumes. The LCC model spans a study period that corresponds to the one determined in the system boundaries (Subsection 7.2.3). A discounted cash flow logic is followed, whereby each cost is assigned to the year in which it occurs and discounted with a discount rate that reflects the opportunity cost of capital. The opportunity cost of capital is estimated by determining the provider's Weighted Average Cost of Capital (WACC), even if in the current business situation not all the cost-generating activities are performed by the provider. If one functional result corresponds to the delivery of a certain functionality during one year, first the costs are calculated over the complete study period and subsequently distributed evenly over all years, by calculation of the equivalent annual cost.

Value outputs can be quantified according to various strategies. Before we describe these strategies, we will clarify how *customer value*, as a multidimensional set of performance indicators, is related to the actual price a customer is willing to pay. The relation between the value components defined in Table 7.1 and the price to be charged to a customer is depicted in Figure 7.2.

On the left of Figure 7.2, we see an example decomposition of value into a set of performance indicators, each of which corresponds to a specific value component. This multidimensional set consists of performance indicators that are mostly not expressed in monetary terms but in non-monetary units (e.g. time units, number of occurences, subjective categories, cfr. Table 7.1). In theory, for each performance indicator PI_j, a monetary estimate for its value can be derived by expressing it into monetary terms, which corresponds to transformation A. For this transformation, $WTP_j^{\max}$, the maximum WTP, is determined for each performance indicator. As highlighted in Section 3.3.1, for investment goods,

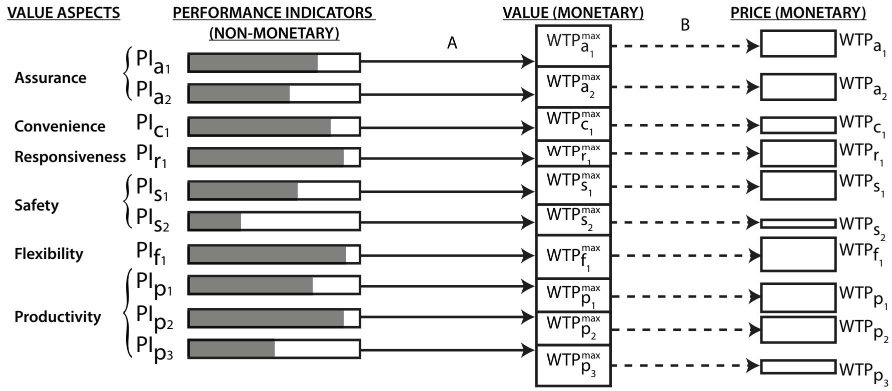

Figure 7.2: Schematic overview of value as a set of non-monetary performance indicators, value as a monetary measure of maximum WTP and price as the actual WTP, whereby the relations between these concepts are determined by transformations A and B.

the maximum WTP can be expressed as the economic impact that a change of PI_j has on the customer's operations. The relation between PI_j and $WTP_j^{\max}$ can be non-linear. For example, for a particular investment good the maximum WTP for one additional percentage point of availability Av can be zero if Av is greater than 95% and €1000 per additional percentage point of availability if $0 < Av < 95\%$. The reason for this could be that increasing the availability of the investment good above 95% has no economic impact whatsoever for the customer, because he does not need its full capacity.

Subsequently, on the right of Figure 7.2, maximum WTP is transformed into actual WTP (price) through transformation B. Price is determined as the sum of all WTP_j, i.e. by adding up all actual WTPs over all performance indicators. Evidently, each $WTP_j^{\max}$ is larger than each WTP_j. As indicated in Section 7.1, transformation B, i.e. the determination of actual WTP, is not the focus of our approach.

In Figure 7.2, already two strategies for quantifying the value per functional result of an investment good can be discerned:

- **Strategy 1:** Quantifying value as a multidimensional set of performance indicators PI_j, most of which are expressed in non-monetary terms, without transformation A. This amounts to quantifying *non-monetary value* $V_{NM} = \{PI_j\}$.

- **Strategy 2:** Quantifying value as the sum of all maximum WTPs, i.e. with transformation A. This amounts to quantifying *monetary value* $V_M = \sum_{j=1}^{X} WTP_j^{\max}$, with X the total number of performance indicators.

The feasibility of Strategy 2, i.e. of expressing value into monetary terms through transformation A, varies from case to case. Some performance indicators might be determined purely by subjective preferences and are difficult to quantify objectively. For example 'evaluation of service experience' might be an important performance indicator for certain products, but not easy to express into monetary terms. For such cases, Strategy 1 can be chosen. But for other cases, quantifying value in monetary terms is possible. As Rese et al. [168] note, customers decide primarily on economic benefits and not on social benefits in industries where there is a high level of competition (as is the case for many investment goods [44, 209]). These economic benefits correspond to the monetary expression of value determined according to Strategy 2. Investment goods are often used by a customer to generate revenues, to reduce costs or to reduce the exposure to risk. For example, for a production machine, increasing its capacity or uptime can lead to extra profits for the customer, and these extra profits are an estimate for the value of extra capacity and reliability respectively. If some external costs can be saved through adaptation of the product (e.g. recuperating heat waste for use in other production processes), quantifying the value for the customer corresponds to estimating the resulting savings. The actual calculation of monetary value from a non-monetary set of performance indicators through transformation A requires a case specific approach, as demonstrated throughout Chapter 8.

According to Strategies 1 and 2, an absolute estimate of value can be determined. Alternatively, value can be expressed in relation to the price of competing offerings, i.e. as an *additional value*. This is represented in Figure 7.3. We recall from Section 3.4.1 that the reason why we want to quantify the value improvement potential of a PSS is that we want to be able to estimate how the provider surplus can be increased by introducing a particular PSS. The provider surplus is equal to $P - C$, with P the price and C the cost. Through transformation B of Figure 7.2 P is determined from V_M. But alternatively, P could be determined from P_{CO}, the price of a competing offering as follows: $P = P_{CO} + \Delta WTP$, with ΔWTP the difference in *actual* WTP between the competing offering and the functional result of the investment good under consideration (i.e. how much the customer is willing to pay extra for the extra benefits the investment good generates in comparison to the competing offering). ΔWTP can in its turn be derived from the additional value that a functional result of the investment good has over the competing offering, i.e. as $\Delta WTP^{\max}$, which is the *maximum* that the customer is willing to pay extra for a functional result over a competing offering. $\Delta WTP^{\max}$ is derived from ΔV_{NM}, a set of

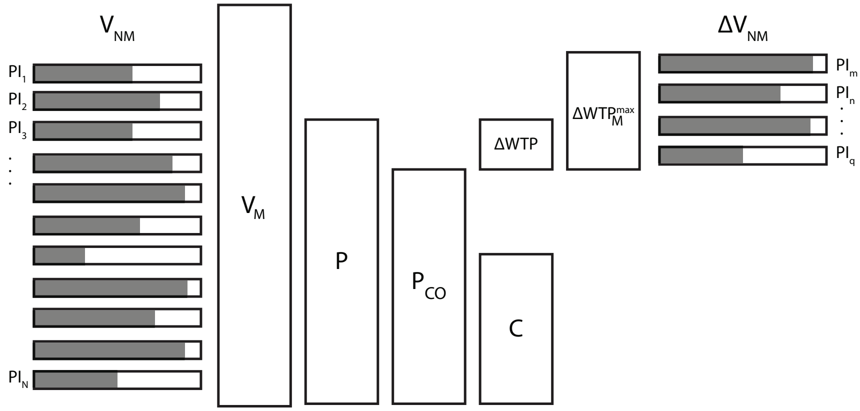

Figure 7.3: Schematic overview of the relation between absolute non-monetary and monetary value on the left side and non-monetary additional value and monetary additional value, relative to the price of a competing offering P_{CO}, on the right side.

non-monetary performance indicators that describe the additional value of the investment good over the competing offering.

Therefore, two additional strategies can be applied to quantify the value per functional result of the investment good:

- **Strategy 3:** Quantifying value by determining P_{CO} and by determining ΔV_{NM}, the additional value of the functional result over the competing offering expressed as a set of performance indicators PI_j, most of which are expressed in non-monetary terms.
- **Strategy 4:** Quantifying value by determining P_{CO} and by determining $\Delta WTP^{\max}$, i.e. the monetary additional value over the competing offering.

Thus, the type of *value outputs* of the model are determined by which value quantification strategy is chosen: mainly non-monetary in Strategy 1, monetary in Strategies 2 and 4 and both monetary (P_{CO}) and non-monetary (ΔV_{NM}) in Strategy 3. Similar to cost outputs, many value outputs (e.g. downtime, number of failures, external savings) can be calculated according to an activity-based logic. The assignment of the impact of each activity on the chosen performance indicators is determined. Many inputs of the cost model are also inputs to the value model (e.g. the mean time to failure of a certain subsystem determines the number of repair operations but also the induced downtime). Aleatory or epistemic uncertainties [65] in the input parameters are represented by statistical distributions or by scenarios (cfr. Section 7.4.2). If a monetary measure of value is calculated, the customer's WACC is used as a discount rate. Non-monetary factors are not discounted.

7.3.2 Input parameters

The input parameters are organized according to five generic types, as shown in Table 7.2. All parameters that are necessary to derive estimates for all the cost and value components (cfr. Subsections 7.2.4 – 7.2.5) should be identified. This categorization allows to discern parameters that are to be considered unchangeable conditions of the business environment (provider and customer specific parameters) from those that are subject to improvement scenarios (logistical, activity and technical parameters). The latter represent the innovation potential of a PSS and are discerned based on the type of improvement scenario that can be realized (e.g. through technical design changes for the technical parameters or through logistical optimization for the logistical parameters, cfr. Section 3.4). Based on customer specific parameters, customer subsegments can be identified for which a PSS has the highest business potential (e.g. for customers with a high WACC or high usage intensity).

7.3.3 Parametric cost and value relations

The parametric relations linking the input parameters to the outputs are determined, following the activity-based logic of the simulation model. An often used equation is the following:

$$\text{Cost}_{\text{year}_i} = \text{Number of events}_{\text{year}_i} \times \text{Impact of one event}$$

In this equation, the number of events can, for example, be the number of failures, the number of usage cycles of a machine tool or the number of cleaning activities. A similuar equation can be used for calculating the value outputs. The impact of one event is determined by the activities that need to be performed (e.g. in case of a technical failure: diagnosis time, probability of first time right diagnosis, repair time, waiting time, coordination time) to solve the problem or perform the task. Thus, if every activity is determined and analyzed for estimating cost or value components, a variant of analytical estimation is applied [153]. Sometimes, a tradeoff between accuracy and efforts is to be made, and approximate cost estimating relationships [173] can be used, that allow to derive estimates by

Table 7.2: Categorization of input parameters in five generic types

Parameter type	**Explanation**	**Examples**
Provider specific parameters	Parameters related to the provider firm, including the time unit costs of the departments/personnel involved.	• Labor cost per hour (service personnel) • Labor cost per hour (project manager) • Provider's WACC
Logistical parameters	Parameters related to the logistical aspects of the service provision	• Average speed of transport • Number of visits • Number of technicians per car
Activity parameters	Parameters that determine which provider resources are used per activity	• Time necessary to diagnose a failure • Probability of first time right diagnosis • Time to repair a failure • Time to coordinate a repair • Time to perform preventive maintenance • Time to clean the system • Material cost in spare parts per repair
Technical parameters	Parameters related to the technical system that trigger activities or that determine the energy or material resource consumption of the investment good	• Failure rates • Probability of secondary damage • Probability of failure detection by Condition Monitoring System • Active and passive energy consumption
Customer specific parameters	Characteristics of the specific application at the customers site	• Distance to the customer's site • Usage intensity • Products per unit of surface area • Revenue impact per hour of downtime • Factors that reflect reduced component lifetime due to polluted working environments • Quality of customer specifications • Customer's WACC

applying empirically determined parametric relations between outputs (e.g. energy cost) and a limited set of inputs (e.g. number of production cycles, average consumption per cycle).

At this point, for the value and cost components that were identified as relevant in the previous step, a calculation strategy has been determined, including the inputs, outputs and the parametric relations between them. Now this model should be fed with data and validated and its outputs should be analyzed.

7.4 Step 3: Data gathering, output analysis and model validation

The objectives of the third step are to collect data that allow to estimate all input parameters, to model the uncertainties and risks as statistical distributions or scenarios, to perform analyses on the outputs of the simulation model and to validate the model.

7.4.1 Sources of information

The following sources of information can be used for obtaining estimates for the input parameters:

- **Historical data.** In some cases, relevant recorded data might be available, e.g. from repair and maintenance reports. Data reliability should be considered with great care. Sometimes enough representative historical data are available to model the aleatory uncertainties in certain input parameters as distributions, through use of statistical fitting techniques (e.g. fitting Weibull distributions for the lifetime of a subsystem on failure data).
- **Measurements.** If sufficient time and resources are available, estimates for important parameters can be derived through dedicated measurements, such as time studies and power measurements. For investment goods used in discrete manufacturing processes, energy measurements can be performed according to the methodology described in reference [100].
- **Internal expert estimates.** In practice, limited availability of reliable historical data often necessitates extensive use of expert estimates. It is important that expert estimates reflect uncertainties and that appropriate distributions are chosen (cfr. Section 7.4.2).
- **External expert estimates.** For determining some inputs, especially the customer specific parameters, expert estimates should be elicited from external sources (customers or other stakeholders). A specific difficulty encountered here is that some information might be shielded because of commercial interests. Therefore, it might sometimes be advisable to elicit estimates that allow to obtain indirect estimates (e.g. eliciting assembly times instead of assembly costs).
- **Financial data.** Some specific financial data is required to derive estimates for certain input parameters, such as the labor cost rate and

the WACC. Mostly, these parameters can be determined in consultation with the company's finance department and depend on the quality of the accounting systems used. Estimating a company's WACC is particularly challenging, as it should not only reflect the current cost of capital, taking into account the company's capital structure, but it should also be risk-adjusted to reflect significant differences among different businesses in a company [30]. Several online sources provide company-specific WACC estimates as well as industry averages [148, 48], and estimates can be derived by looking for similar companies in similar industries. If in a particular case no certainty can be assumed on some financial parameters used in the model, uncertainty distributions can be introduced and by analyzing their impact on the output variation, the need for extra data gathering efforts can be identified.

7.4.2 Uncertainties and risks

Uncertainties and risks in the input parameters can be modeled by distributions or scenarios, according to the following guidelines:

- For modeling *expert opinions*, often-used distributions are the Uniform, PERT, Modified PERT, discrete, normal or triangular distributions [229]. In case there is no indication which value is most likely within a certain interval, the uniform distribution is the preferred choice. In case three point estimates can be elicited (minimum, most likely and maximum value), the PERT distribution is usually appropriate.

- *Correlation* between input parameters can be modeled by setting a rank order correlation parameter, or by applying the envelope method, lookup tables or conditional logic [229]. If this is not done, the output distributions can be distorted by unrealistic combinations of inputs.

- *Failure rates* during each year of the study period can be modeled as Poisson distributions (if a time invariable failure rate is presumed) or can be determined based on computations of the consecutive times to failure for a given subsystem or component (e.g. using Weibull distributions based on historical failure data).

- A very important choice that needs to be made is deciding on which parameters will be used to define scenarios. Sometimes it is better to *define a set of scenarios* for a certain input parameter A instead of modeling it as a single distribution. This is the case if A is highly correlated with (one of) the model outputs and if insight on the influence of other input parameters on the output variation is blurred by the uncertainty in A. Especially if such a dominant parameter A is customer specific, it is advisable to partition it into a set of scenarios, representing customer subsegments. Then, for each subsegment, an analysis can be performed to identify the most important technical, logistical and activity parameters. Scenarios can also be defined based on combinations of input parameters (e.g. high usage intensity/high revenue impact of downtime versus low usage/impact) or by assuming certain outcomes for input parameters that represent a significant aleatory uncertainty (i.e. uncertainty that is irreducible through further study). Examples of the latter are parameters that indicate whether relevant legislation changes or future electricity prices.

7.4.3 Output analysis and validation

The process of gathering data, modeling uncertainties and analyzing the outputs of the model is in practice iterative. Through a sensitivity analysis, e.g. by calculating correlation measures such as Spearman's rank correlation coefficient, the inputs that are most correlated with the outputs are determined, and priorities for extra data gathering efforts can be set. Wherever possible, estimates for the same parameters should be obtained from independent data sources and in case there are large discrepancies, more information can be pursued. If reliable data are available in the company's accounting system for specific customers/projects, the corresponding customer specific inputs can be fed into the simulation model to compare the resulting output distributions with the actual recorded costs. Further validation is also possible by presenting and discussing preliminary results to different experts and stakeholders involved in the study and to adapt estimates if needed.

For presenting the results, the following types of graphical representations are useful:

- *Box plots, probability density functions (pdf)* or *cumulative distribution functions (cdf)* of the resulting LCC or value outputs. For each scenario determined in Section 7.4.2, a separate box plot, pdf or cdf can be drawn.
- *Pie charts* of the averages and possibly of the 10th- and 90th-percentile, whereby a decomposition of cost or value into the constituent components is possible, or, for example, into categories such as labor, energy, material and transportation costs.

- *Tornado charts* representing the rank order correlations of inputs and output(s) or the range of the conditional average output in function of input parameter variations.

After this step, the simulation model should reflect the actual cost and value per functional result of the investment good in the current situation, whereby the latter is presented as a multidimensional quantity consisting of all relevant performance indicators. In the next step, the improvement potential in cost and value of a PSS is to be analyzed, by identifying a set of improvement scenarios.

7.5 Step 4: Improvement scenario analysis

In the last step, improvement scenarios for cost and value are identified and their impact is quantified. Subsequently, conclusions can be derived on the business potential of a PSS.

7.5.1 Identifying improvement scenarios

A set of improvement scenarios is to be identified, whereby each scenario describes a specific, realistic and quantifiable idea on how cost can be reduced or how value can be added for a customer (sub)segment in comparison to the current situation. At this stage, different specializations within the company can be involved (e.g. technical, operational and marketing experts), as well as lead users or other stakeholders (e.g. subcontractors, industry experts).

The improvement scenarios can be derived by screening all technical, logistical, activity and customer specific parameters (as defined in Section 7.3.2) and formulating ideas on how these parameters can be changed to improve value and/or cost. The type of improvement scenario depends on the type of parameter:

- **Technical parameters:** most changes to these parameters can be implemented through technical product changes. An important class of improvement scenarios is related to an increased energy and resource efficiency, which, for discrete manufacturing processes, can be realized by applying one of the generic energy and resource efficiency increasing techniques listed in reference [58]. Another major source of improvement can be found in reliability enhancements, e.g. by increasing the mean time to failure of system components.

- **Logistical parameters:** improvement scenarios related to the logistical parameters can include optimization of the service organization (e.g. optimal service technician scheduling and routing [112]), opportunistic maintenance (performing preventive maintenance tasks when corrective action is required and thus saving transportation costs and downtime [247]), inventory optimization for spare parts [219], etc.

- **Activity parameters:** scenarios related to activity parameters can be diverse, including streamlining of individual service activities, improving the maintainability of the technical system, improving the diagnosis effectiveness (e.g. through remote condition monitoring), choosing materials such that the system can be cleaned more efficiently, etc.

- **Customer specific parameters:** scenarios related to customer specific parameters are not stemming from technical or operational changes, but rather entail a focus on specific customer (sub)segments for which the value of a PSS is maximal or the cost is minimal. The customer (sub)segments thus identified promise to have a larger profitability (i.e. a larger sum of provider and customer surplus) and can be prioritized for the company's business development strategy.

Apart from the improvement scenarios confined within the system boundaries, value might be added by enabling *external cost savings or revenue increases*, such as innovations within the FHM of the investment good (cfr. Section 4.3) or in the customer's processes (cfr. Section 6.4).

7.5.2 Analyzing improvement scenarios

Once the improvement scenarios are identified, they can be analyzed quantitatively through a combination of simulation and scenario analysis, and presented graphically as described in Section 7.4.3. For this analysis there should be a clear description of the *base case scenario*: each improvement scenario presupposes that a certain existing situation is improved for a certain customer (sub)segment (e.g. for all customers that own a system of an older generation and that use it intensively). The influence of the improvement scenario on the average cost/value per functional result as well as on the cost/value variation should be investigated.

7.5.3 Drawing conclusions

Based on the results of the previous analysis, conclusions can be derived concerning the value or cost improvement potential of a set of PSS options. Each individual improvement scenario represents a certain business potential and can be implemented through a range of PSS options. If, for example, a cost reduction improvement scenario is identified in the active energy consumption of the investment good, the possible PSS models to tap this potential can be one of the following:

- A first PSS option in which the energy cost is internalized in the provider's offering and the investment good is sold per hour of availability, per hour of use or per functional result, including energy consumption. In the nomenclature of Chapter 5, this implies the implementation of an integrated availability-, usage- or performance-based PSS.
- A second PSS option whereby an additional *energy improvement service* is sold separately from the product offering. This service could encompass a contract over several years whereby the energy efficiency enhancement investments are covered by the provider, the energy consumption is monitored and compared to the base case scenario and the avoided energy cost is shared between customer and provider. In the nomenclature of Chapter 5, this corresponds to a segregated offering whereby the energy improvement service is sold with a performance-based effect-oriented (cost) or solution-oriented (reduction in energy consumption in kWh) revenue mechanism.

Thus, a matrix can be derived that links the improvement scenarios on the horizontal axis with the PSS options on the vertical axis, a cross indicating that a scenario can be 'realized' through a corresponding PSS option (cfr. Figure 7.1). The realization of an improvement scenario by a PSS option means that in that particular PSS option, the provider benefits financially from implementing the corresponding scenario. For the previous example of an improvement scenario related to the active energy consumption, both PSS options mentioned realize this particular improvement scenario. But other improvement scenarios (e.g. related to the maintainability of the system) are more likely to be realized by the first PSS option than by the second, because the first option internalizes more cost and value components in the PSS provider's offering.

The information thus obtained provides decision makers a clear overview of the improvement potential in cost and value of a set of PSS options. Of course this is not the only information that will lead to a choice for a particular PSS. Other criteria to determine whether a PSS that taps a large innovation potential will be suitable are its inherent risks, the ability of the provider company to counter all challenges related to the transformation towards PSS provider (such as cultural issues, the acquisition of new capabilities, etc. [129]) and an evaluation of how the implementation of a PSS will influence competitive dynamics and whether it will be able to expand the customer base (cfr. Mechanisms 3 and 4 of Section 3.4.1).

The type of management decisions that can be supported by application of the proposed methodology are summarized in Table 7.3. These decisions can be subdivided in two categories: strategic and operational.

Table 7.3: Summary of management decisions that can be supported through application of the proposed methodology

Strategic decisions	**Operational decisions**
• Which PSS option should be selected, based on its cost and value improvement potential?	• Which activities should be streamlined to reduce cost or increase customer value in a PSS?
• Which market segments should be primarily targeted in a specific PSS model?	• How to determine a suitable pricing basis for selling a PSS and which parameters should be included in a pricing formula?
• Which technical parameters should be improved through R&D efforts to enhance the profitability of a PSS?	• What are the main performance indicators that allow to assess the performance of a PSS?

7.6 Conclusions

In this chapter, a novel methodology to evaluate the business potential of a PSS both in terms of cost reduction and value improvement was presented. At its start, it is important to specify the scope and goal of the assessment: which functional results are considered, which cost and value components are taken into consideration and which restrictions to market segments and system boundaries are set. Through a combination of Monte Carlo simulation and scenario analysis, the business potential of value or cost improvement scenarios can be systematically quantified. By linking the improvement scenarios to PSS options, conclusions can be derived on the PSS options with the highest business potential. The simulation model and scenario analysis are organized according to the provided generic input parameter classification, and some guidelines are presented on how appropriate outputs can be chosen (that correspond to the selected value quantification strategy), how to gather and validate data for the estimation of input parameters, how to account for relevant uncertainties and risks as well as how to analyze and represent the results.

The main strength of the proposed methodology is that it allows to analyze the PSS innovation potential in cost and value, taking into account uncertainties and risks. Its main shortcoming is related to the fact that only the mechanisms 'cost reduction' (1) and 'value improvement' (2) are analyzed quantitatively, excluding the mechanisms 'changes to the competitive environment' (3) and 'customer base expansion' (4). In order to account for these two mechanisms, apart from quantifying value and cost a quantification of price (actual WTP) is necessary. As argued in Section 7.1, pricing research requires extensive, time-consuming survey work to elicit the actual WTP of (potential) customers and therefore a choice was made for the quantification of the maximum WTP (value), which is – for investment goods – often quantifiable as extra revenue or lower costs and can be determined in a faster and easier way than actual WTP.

To verify the transferability of the proposed methodology, its application on five industrial case studies is demonstrated in the next chapters.

Chapter 8

Quantifying the business potential of a PSS: Case studies

In this chapter, the application of the methodology described in Chapter 7 is demonstrated on five of the cases that were introduced in Chapter 2. In sections 8.1, 8.2, 8.3, 8.4 and 8.5 the descriptions are provided for Cases α, β, γ, δ and λ. The cases presented in this chapter serve as various illustrations of the different steps in the methodology of Chapter 7. In order to safeguard the quality of the presented case study research, particularly with regards to traceability, a substantial amount of detailed information is provided for each case. However, to improve the readibility of this chapter, several elaborations are presented in appendix (Appendices B, C, D and E for Cases α, β, γ and δ respectively). At the end of each case, generic conclusions are formulated about the applicability of the methodology of Chapter 7 and about the main lessons learned within that particular case. Section 8.6 presents a cross case analysis and discusses the extent to which the presented cases allow to validate the methodology of Chapter 7. The conclusions of this chapter are formulated in Section 8.7.

8.1 Case α: Traction elevators

This section covers a case study performed for Company α, a manufacturer and service provider in the elevator industry. In Section 8.1.1, some background is presented on elevators, the elevator industry and Company α. In Sections 8.1.2 to 8.1.5, application of the four steps of the methodology of Chapter 7 are discussed.

8.1.1 Background: traction elevators

Elevators can be of the hydraulic type, if the car is moved by a hydraulic cylinder, or of the traction type, if it is driven by an electric motor. Traction elevators are either geared or gearless, depending on whether a reduction gear is used to drive the car. The most common technology in use today are gearless traction elevators [50]. An important technological innovation emerged in the mid 1990s: machine roomless elevators [207]. While for a traditional elevator the motor and control panel are located in a machine room above the lift shaft, the application of permanent-magnet synchronous motors in combination with a variable voltage, variable frequency (VVVF) drive allows to reduce the size of these systems drastically such that they can be fitted directly in the elevator shaft. The main advantages of this change are a substantial reduction of energy consumption, the fact that no oil is used, the use of more efficient and safe installation methods and the savings in usable construction space [207].

A gearless, machine roomless traction elevator, which is the focus of this case study, consists of the following main subsystems:

- The *elevator car* consists of a frame, a car door, a roof, floor and side walls.
- The *drive system* consists of an electric motor, a frequency converter, cables and a traction sheave.
- The *landing doors* are located on each floor of the building.
- The *counterweight* equals the weight of the elevator car, the sling and some (mostly 50%) of the elevator's rated capacity. Thanks to this counterweight, enough tension is created in the suspension system and the energy consumption is reduced.

For confidentiality reasons, most of the numerical values presented in this section are expressed relatively or, if monetary values are provided, they were multiplied with an unspecified scale factor.

- The *control panels and displays* are the interface to the users, in the car and on each floor. In each elevator, a phone is present that allows the users to contact the helpdesk in emergency situations.

Several international standards prescribe various aspects of elevator design, operation and maintenance, such as the European standards EN-81-1/2 and EN 13015. According to EN 13015, it is the responsibility of building owners that preventive maintenance of their elevators is carried out by a maintenance organization, that can either be the manufacturer or a specialized maintenance company.

According to estimates of one of the major global manufacturers, Kone, in 2008 9,1 million elevators were in operation worldwide, representing an annual total market of €34 billion, 40% of which is related to sales of new equipment and 60% to maintenance and renovation [110]. For many elevator manufacturers, the service business generates more than half of the income and the majority of the profits [55].

Company α is a manufacturer and service provider of elevators. Its main reasons to consider a PSS are the following:

- to 'pool' the sales of a new elevator with a service contract over a long term for certain customer segments and thereby reduce price based competition in the sales of new elevators
- to be able to tap the opportunities offered by optimizing the elevator's design over its complete lifecycle
- to devise an offering that is a closer match to the needs of its customers (e.g. whereby maintenance is paid based on the usage intensity of the elevator)

8.1.2 Step 1: Goal and scope definition

Customer segments

After discussions with the central project team of Company α, it was decided that a suitable customer segmentation basis is the *application type*. Thus the following segments were identified:

- Healthcare (e.g. hospitals and retirement homes)
- Residential buildings
- Office buildings
- Industrial buildings

- Public sector buildings

The attractiveness of a PSS model was discussed for each of these segments, and it was decided to focus the quantitative analysis on the segment 'Healthcare', for the following reasons (cfr. the criteria listed in Section 7.2.1):

- This segment represents, for Company α, a large market size, since Company α has a large installed base in Belgian hospitals and retirement homes.
- This segment consists of customers that typically have many elevators per building.
- The consequences of malfunction are significant and the technical staff of these customers do not consider the operation or maintenance of elevators as a core competence. Therefore, it was estimated that customers in this segment would be willing to outsource responsibilities related to their stock of elevators.

Basis of evaluation

Functional results on different levels of abstraction for an elevator are presented in the second column of Table 4.1 on page 61. Company α representatives expressed that they did not have the capabilities nor the ambitions to develop other means of vertical transportation (e.g. escalators) or flow optimization (e.g. signaling). Therefore the solution-centric functional result (*provide an elevator service between specified floors of building A during one year*) was chosen as the basis of evaluation (assuming that a traction elevator is chosen as a solution).

System boundaries

Subsequently, the system boundaries were determined, as indicated in Table B.1 of Appendix B. Each of these boundaries was derived from discussions with the central project team of Company α and defines a justifiable set of assumptions for the evaluation model.

Cost components

The Cost Breakdown Structure is depicted in Figure 8.1.

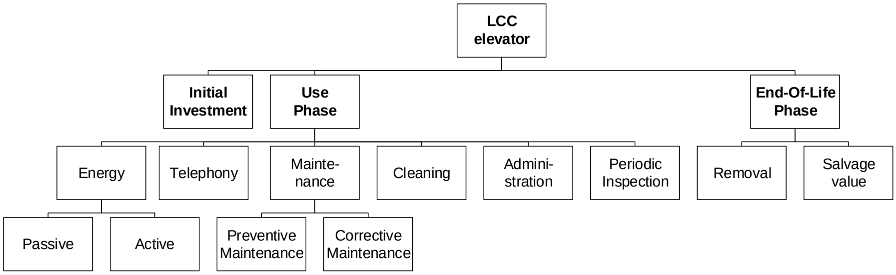

Figure 8.1: Cost Breakdown Structure for Case α.

Value components

The value components and corresponding performance indicators identified are presented in Table 8.1. The indicators displayed in bold were chosen in consultation with the company representatives for further analysis, because they are quantifiable, represent an important aspect of the elevator's value for the customer and were identified as interesting with regards to potential improvement scenarios.

Table 8.1: Value components and corresponding performance indicators for Case α.

Value aspects	**Value components**	**Performance indicators**
Assurance	Competence of provider personnel	• Number of faulty diagnoses [number]
	Conformity to norms and standards	• Conformity to elevator standards [binary]
Convenience	Ease of operation	• Elevator ride quality, measurable according to ISO 18 738 [subjective score] • Waiting and journey time of hospital personnel [hours]
Responsiveness	Responsiveness to emergencies	• Intervention time (e.g. for liberating trapped users) [hours]
	Responsiveness to regular service requests	• **Diagnosis time [hours]**
Flexibility	Ability to facilitate external cost savings or revenue increase	• **Effect on thermal losses through elevator shaft [€]** • Effect on property value [€]
Productivity	Reliability	• **Unplanned and planned downtime [hours]** • **Number of failures [number]**
	Maintainability	• **Time to repair for all failure modes [minutes]**
	Capacity	• Handling capacity [persons per hour]

8.1.3 Step 2: Model development

The model to quantify the cost and value per functional result of a traction elevator was constructed according to the following logic:

- The *cost per functional result* was expressed as the Equivalent Annual Cost (EAC) of owning and operating an elevator in a hospital environment, reflecting the sum of all cost components of Figure 8.1.
- The *value per functional result* was quantified according to Strategy 1 of Section 7.3.1, i.e. by expressing value as a set of non-monetary performance indicators. The members of the central project team of Company α decided that translating these indicators into a maximum WTP (i.e. a quantification of monetary value according to Strategy 2) was impeded by a high variability of the maximum WTP of these performance indicators between customers and that such a quantification was not expected to generate additional insights.

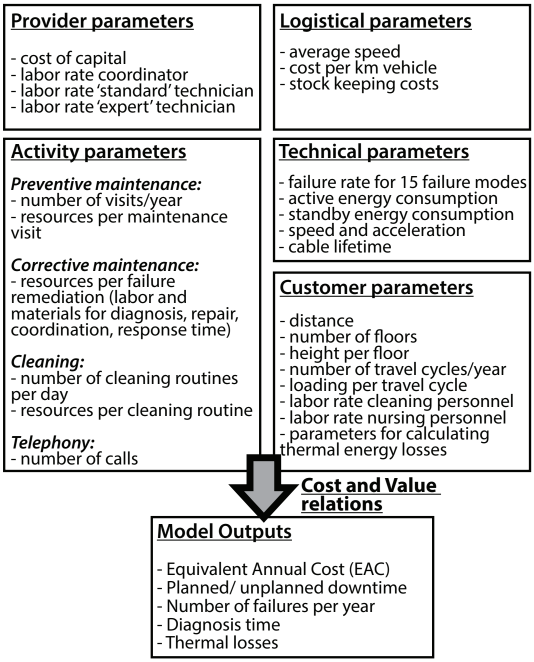

Figure 8.2: Model structure for Case α.

The structure of the simulation model with input parameters in different categories is depicted in Figure 8.2. This model was constructed in a spreadsheet environment, using a statistical software add-in for running Monte Carlo simulations and analyzing the results (ModelRisk™).

The *parametric cost and value relations* that link the outputs to the inputs were determined as follows:

- Fifteen *failure modes* for an elevator were identified (e.g. mechanical failure of doors, motor failure, display failure). For each failure mode, consecutive times to failure were calculated by modeling the failure rate as an exponential (time-independent) or as a Weibull distribution (time-dependent). Then, failures were assigned to the years in which they occur. After discussions with product and maintenance specialists in Company α, it was decided to make the occurence of failures only dependent on the elapsed time period and not on the number of travel cycles. The main reasons for this choice are the fact that historical data on the dependency of the failure rate on the number of travel cycles were not available and the fact that for several failure modes (e.g. electrical problems) a correlation of the failure rate with the usage intensity is not expected. However, for certain failure modes (e.g. mechanical problems of the door), a correlation between these parameters is expected, which is not taken into account here due to the lack of reliable data. Each failure induces a particular impact on cost and on the performance indicators diagnosis time, downtime, number of failures and time to repair. This impact was calculated by adding or multiplying a set of activity parameters (e.g. activity duration drivers, material costs per failure mode, spare parts holding costs per failure mode).

- A conditional logic was programmed in the model that represents the diagnosis effectiveness. To each failure mode, a probability that the first diagnosis is successfull was assigned. Two types of technicians are taken into account: ‘expert’ technicians and ‘standard’ technicians. The assumption was made that the first category, that represents a higher labor rate, is to be summoned in the event of a non-conclusive first diagnosis and for certain complex repairs.

- *Logistical costs* were determined based on the distance between the service technician’s previous location and the customer site. Vehicle costs (including vehicle ownership, maintenance, fuel consumption and insurance) were discerned from labor costs (time spent by service technician in transport). Different distances were taken into account for ‘expert’ technicians versus standard technicians.

- Apart from a failure mode *premature wear of elevator cables*, an additional ‘failure mode’ was modeled: *cable replacement due to the cables reaching their maximum lifetime.* This maximum lifetime is the minimum of either 1,2 million travel cycles or 8 years of operation.

- The number of travel cycles determines the *active energy consumption.* To determine the active energy costs of an elevator, the parametric relations that express the total energy consumption for one reference cycle were used as defined by the standard VDI 4707-1 [227], which relates the energy consumption to the rated load and travel distance. Eight different combinations of elevator velocity, acceleration and loading were determined as measurement scenarios. *Passive energy consumption* was measured during rest by gradually switching of all power consuming subsystems, such that the standby power of all subsystems (e.g. lighting, transformer, battery charger, safety circuit) could be determined.

- The thermal loss through the elevator shaft was calculated according to the approach described in Section B.2 of Appendix B.

- Preventive maintenance costs were determined by the number of visits per year and the 'impact' per visit (labor hours, material consumption).

8.1.4 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table B.2 of Appendix B, the main information sources used are listed in the four categories proposed in Section 7.4.1.

The measurement method that was applied to determine the active and passive energy consumption of the elevators under different conditions (velocity, acceleration, loading) and some results of its application are presented in Section B.3 of Appendix B.

Uncertainties and risks

As explained in Section 7.4.2, in the presented approach uncertainties and risks are modeled either as statistical distributions or as scenarios. For each scenario, a separate output distribution (e.g. of the life cycle cost per functional result) is determined. Especially customer specific input parameters are suitable for defining a set of scenarios, each representing a customer subsegment.

For Case α, the main parameter chosen to discern scenarios is the usage intensity. After analyzing the recorded number of travel cycles for 58 elevators in a large hospital (cfr. Table B.2), a decision was made to discern three scenarios, corresponding to three usage classes of elevators: low, medium and high usage intensity. Within each of these three scenarios, the number of travel cycles per year was fitted as a bounded normal distribution on the available data according to maximum likelihood estimation. If no scenarios would have been defined, the uncertainty of the parameter 'number of travel cycles' would have dominated the uncertainty in the outputs (e.g. equivalent annual cost of owning and operating an elevator) and the influence of the other input parameters would have been obscured. Therefore, discerning three usage class scenarios is preferable over modeling the uncertainty around the number of travel cycles as a single distribution.

The statistical distributions that represent the uncertainties in the input parameters were chosen according to the guidelines provided in Section 7.4.2.

The most important and noteworthy choices are explained in Table B.3 of Appendix B.

Output analysis and validation

Some results of the output analyses for Case α are presented, chosen such that they are most suitable for demonstrating the proposed methodology and such that they are most relevant for the improvement scenario analysis in Section 8.1.5. Subsequently, the measures taken to verify and validate the simulation model are discussed.

The output distributions were obtained by running the Monte Carlo simulation model with 5000 iterations. Some results are presented in Figures 8.3 to 8.6. While these figures are all related to the high use scenario (highest number of travel cycles), analogous results were derived for the other scenarios (low and medium use). For confidentiality reasons, the scales of the X-axes of all figures have been adapted with a non-specified scaling factor. After the initial output analysis, the following conclusions were derived:

- In Figure 8.3, all main cost components of the LCC of an elevator are presented in separate boxplots. This manner of presenting the results of the LCC analysis was perceived as insightful by Company α representatives. LCC is expressed as the average equivalent annual cost of owning and operating an elevator in a hospital environment and is determined mainly by the maintenance costs (preventive and corrective) and, surprisingly for the central project team of Company α, by the cost for cleaning the elevator car interior. The energy costs are less influential than initially thought.

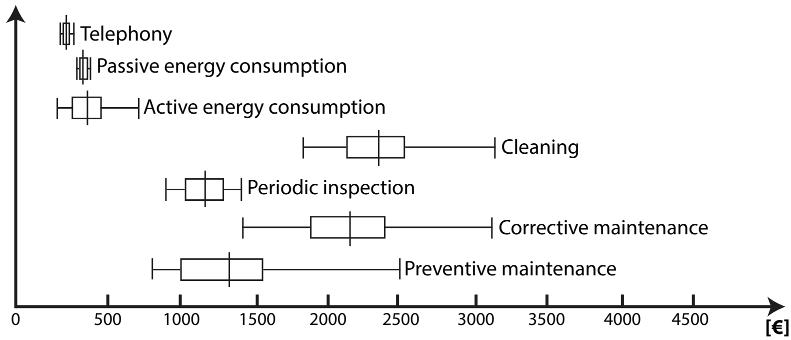

Figure 8.3: Equivalent annual cost of owning and operating a high-use elevator in a hospital environment decomposed into cost categories.

- The key factors that drive the variation in LCC of an elevator are the number of travel cycles, the distance to the customer's site and the number of floors of the building. This was determined by calculating rank order correlations between all inputs and the output LCC.
- As indicated in Figure 8.4, the corrective maintenance costs of an elevator are, on average, for 78% determined by only three of the fifteen failure modes (for the high use scenario). This finding illustrates the Pareto principle.
- On average, 49% of the downtime of an elevator is planned (i.e. due to preventive maintenance or to failure mode $FM15$, which corresponds to replacing the cables after a certain time interval has passed or a number of travel cycles has been reached, cfr. Figure 8.5). Preventive maintenance and five failure modes are responsible for 97% of the downtime.

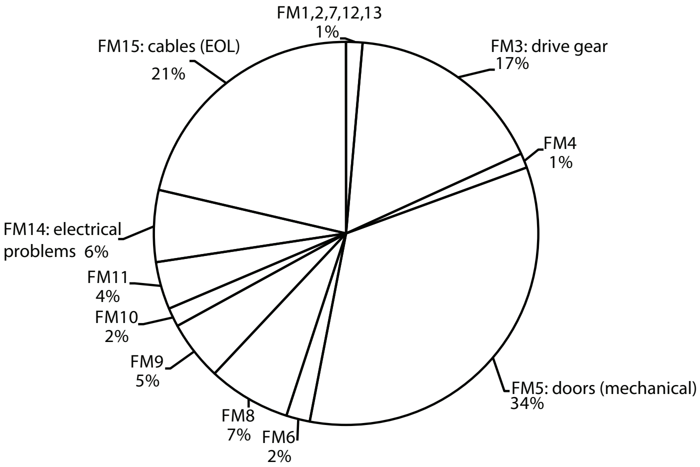

Figure 8.4: Average equivalent annual corrective maintenance cost of a high use elevator in a hospital environment, decomposed into the fifteen identified failure modes.

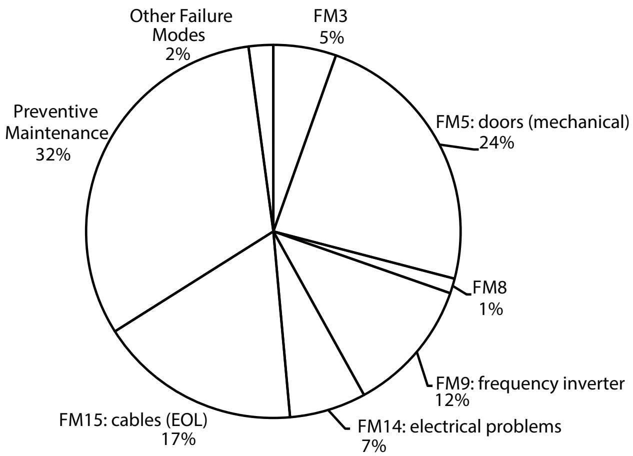

Figure 8.5: Average yearly downtime of a high use elevator in a hospital environment decomposed into the corresponding causes of downtime (preventive maintenance or one of the fifteen failure modes).

- As can be seen from Figure 8.6, if the maintenance costs (preventive and corrective) are decomposed into different cost categories, the logistical costs ('lost' labor hours and vehicle costs) are substantial (they represent 26% of the total costs on average). Over the total population of customers, these costs vary significantly (depending on the distance to the customer).

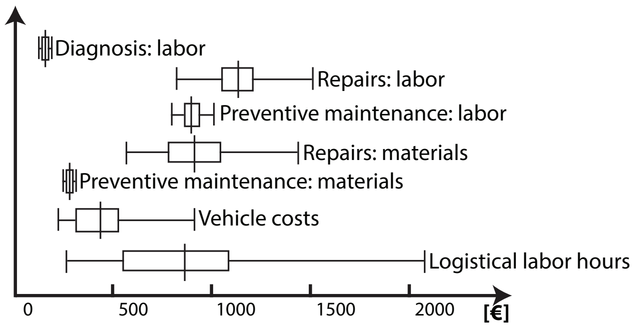

Figure 8.6: Equivalent annual maintenance cost of a high-use elevator in a hospital environment decomposed into cost categories.

- As can be seen from Table 8.2, half of the failures that occur over the lifetime of an elevator are related to mechanical issues with the doors. Together with errors of the display and control panel, this failure mode accounts for almost 80% of the elevator's faults. The performance indicator *number of failures* was identified as critical for the *perceived* reliability of the elevator.

Table 8.2: Average number of failures over a period of 20 years for a high use elevator, divided per failure mode (expressed as a percentage of the total average number of failures over this period).

Failure Mode	**Relative share of the average total number of failures over 20 years**
FM5: doors (mechanical)	50%
FM8: display/control panel	29%
FM6: car lighting	13%
FM9: frequency inverter	2%
Other failure modes	6%

- The yearly equivalent maintenance cost of a high use elevator (in €) can be expressed by means of a linear regression (Ordinary Least Squares) as follows:

$$EAC = A + B \cdot f + C \cdot d + D \cdot tc \tag{8.1}$$

  In this formula, A, B, C and D are constants, f is the number of floors in the building, d is the distance in kilometers between Company α and the customer's site and tc is the yearly number of travel cycles. The coefficient of determination R^2 for this regression model is 0,62[2]. With this coefficient of determination, the suitability of Formula 8.1 to predict the maintenance cost per travel cycle seems limited. One of the reasons for the relatively low coefficient of determination are the modeling choices made, whereby failures are only made dependent on the elapsed time period and not on the number of travel cycles, cfr. Section 8.1.3. Similar formulas were defined for medium- and low-use elevators, but there the coefficient of determination was significantly lower (0,43 and 0,31 respectively).

For validating the simulation model, the following measures were taken:

- The results were discussed in detail with the members of the central project team of Company α, whereby illogical or counter-intuitive (intermediary) results were listed and selected for further data gathering and/or model checking efforts. Three iterations were needed to ensure that all issues were resolved.

- The input data related to the failure rates and impacts for calculating the corrective maintenance cost were estimated independently by two data sources: an R&D expert and subsequently a team of a service coordinator and two service technicians. In case there were large discrepancies between both estimates, the central project team decided for each parameter which estimates were to be selected and where the uncertainty needed to be adapted (e.g. decreasing the minimum and increasing the maximum estimate for a certain parameter).

8.1.5 Step 4: Improvement scenario analysis

Based on the guidelines provided in the methodological description (Chapter 7), a set of improvement scenarios has been identified and analyzed quantitatively.

[2] R^2 only indicates how well the data points derived by the Monte Carlo model of Figure 8.2 follow the linear relation of Equation 8.1, it is not defined in relation to actual recorded maintenance costs.

Identification of improvement scenarios

The main improvement scenarios are presented in Table 8.3, organized according to the type of input parameter.

Table 8.3: The main improvement scenarios to reduce cost or improve value identified within Case α.

Parameter category	Description of improvement scenario
technical parameters	***A1***: increasing the lifetime of the cables by 25% (expressed in number of travel cycles)
	A2: reducing the active energy consumption by adapting the counterweight: by measuring the historical loading of the elevator car during a few weeks in a specific usage pattern, the counterweight can be adapted such that the total energy consumption will be minimized for the specific usage pattern of the elevator.
	A3: reducing thermal losses through the elevator shaft by controlling the openness of elevator vents during standby time, such that heat from inside the building does not dissipate through the shaft
	A4: renovating outdated elevators with Ward Leonard drive system to a new drive system
	A5: increasing the reliability of the doors such that the number of failures is halved.
logistical parameters	***A6***: decentralizing the maintenance organization such that the maximum distance between each customer and the corresponding service hub is 100km.
	A7: opportunistic maintenance: preventive maintenance tasks are performed as much as possible at a time when diagnosis or repairs are scheduled
activity parameters	***A8***: increasing the effectiveness of diagnosis such that in 50% less cases additional diagnosis is required
	A9: reducing the time required for cleaning the elevator by 50%, by optimizing the design and materials used in the interior of the elevator car
	A10: stationing a service technician permanently at the customer's site (if enough elevators are installed) to make sure that the logistical costs are reduced and that the downtime can be minimized by a faster response time.

Analysis of improvement scenarios

The results of the quantitative analysis of the improvement scenarios identified in the previous step are presented in Table 8.4.

Table 8.4: The main results of the quantitative analysis of the improvement scenario examples of Table 8.3.

Parameter category	**Main results of the quantitative analysis**
technical parameters	***A1***: Increasing the lifetime of the cables by 25% reduces the average cost of maintenance of an elevator with 9,8% and reduces the planned downtime with 4,3%, for the high use scenario. ***A2***: For an average high use elevator, customizing the counterweight can save up to 11,9% of the total yearly energy cost (as determined by an analysis of the power and time measurement, cfr. Figure B.1). However, after the adjustment the technicians should check whether the traction remains within the bounds specified by the applicable standards. ***A3***: Based on the calculation method in Section 8.1.3, on a typical high use elevator in a hospital environment €1000–3000 could be saved on a yearly basis by controlling the openness of elevator vents, with a one time investment of about €3500–4000 and a yearly maintenance cost of about €300. The savings are higher for elevators that have large doors and that are not often used, in buildings with a large number of floors and bad insulation. Another important factor is the ventilation opening of the shaft (in %). In old buildings in Belgium, the legal requirement was 4%, but recently this changed to 1%. It is estimated that many building still have a 4% opening and therefore a larger thermal loss. ***A4***: Renovating old elevators with Ward Leonard drive system can save €1800-2200 in yearly energy cost, which is a reduction of about 67% in energy cost. But the discounted payback period can vary between 6 and 15 years, depending on the remaining lifetime of the current installation. ***A5***: If the reliability of the doors can be increased such that there are 50% less occurences of failure mode $FM3$, that would imply on average a 17% reduction of the corrective maintenance cost, a 12% reduction of the yearly downtime and a 25% reduction of the yearly number of failures.
logistical parameters	***A6***: Decentralizing the maintenance organization can reduce the average maintenance cost per elevator with 20,9%. From this maximum savings, the extra storage and real estate costs of a new service hub need to be subtracted, that depend on the number of elevators per region. ***A7***: Opportunistic maintenance can save on average 14,5% of the total maintenance cost and can reduce downtime with 32% (all planned). In case scenario A6 is realized first, the cost and downtime improvement potentials are 7,3% and 16% respectively.
activity parameters	***A8***: More effective diagnosis can reduce the maintenance cost on average by 1,5%. ***A9***: A 50% efficiency gain in elevator cleaning would lead to a reduction with 6% of the total cost of owning and operating an elevator for a hospital. ***A10***: The main advantage of permanently positioning a service technician at the site of large customers is that the elevator's downtime can be reduced. According to calculations with the simulation model, in this way 29% to 59% of the unplanned downtime can be eliminated, depending mainly on the distance between Company α and the customer's site. Another advantage of this scenario is that it allows a better coordination with the customer about the planned downtime. The cost advantages (savings in logistical costs) of this improvement scenario are highly dependent on the number of elevators present at the customer's site. The total 'handling capacity' of one full time service technician was calculated to be about 100 elevators. At full capacity, the average maintenance cost saving per elevator of this scenario is 26%.

Conclusions for Case α

After the improvement scenarios are analyzed quantitatively, they can be related to PSS options $PSS_{\alpha1}$ to $PSS_{\alpha7}$ (represented in Figure 6.3 and described in Table 6.3). An inquiry was carried out to identify which of the PSS options can provide a direct link between the financial return for Company α and the performance improvement stemming from the realization of a corresponding improvement scenario. If there is a direct link between a PSS option and an improvement scenario, this means that Company α's revenues are increased or its costs are decreased directly if the improvement scenario is implemented. Therefore, Company α has an incentive to realize this scenario to a maximum extent. For example, an improvement scenario that allows to decrease the spare part consumption of a certain failure mode by using more reliable components, can only be realized by a PSS option whereby spare parts are sold in an integrated package according to a availability-, usage- or performance-based revenue mechanism. In other words, it is said that this PSS option *allows to tap the improvement potential* of this particular scenario.

As can be seen from Table 8.5, each of the seven identified PSS options allows to tap the innovation potential of one or more of the improvement scenarios. In none of the identified PSS options, there is a direct link between Company α's financial return and the performance improvement due to scenario $A3$. At first sight, no realistic PSS option could be identified whereby the thermal losses through the elevator shaft are included in the provider's offering. However, if the temperature inside and outside the building and the air velocity inside the elevator shaft can be monitored, the actual savings due to the implementation of $A3$ can be calculated. This would in its turn allow to sell the add-on product elements (control units of the ventilation grid, smoke detectors) according to the amount of energy that is saved.

The reason why only PSS options whereby maintenance and spare parts are sold according to a UB revenue mechanism are considered to tap scenario $A10$ is that we presume that the number of travel cycles can in principle be increased if the downtime is reduced. If maintenance and spare parts are sold at a fixed yearly sum, irrespective of the number of travel cycles, there is no direct link between Company α's financial return and the realization of these scenarios.

Table 8.5: Matrix linking the improvement scenarios $A1$ to $A10$ of Table 8.3 with the seven PSS options for Company α

	A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**
$PSS_{\alpha 1}$	X	X			X	X	X	X	X	X
$PSS_{\alpha 2}$	X				X	X	X	X		X
$PSS_{\alpha 3}$	X				X	X	X	X		X
$PSS_{\alpha 4}$	X	X			X	X	X	X		X
$PSS_{\alpha 5}$	X				X	X	X	X		X
$PSS_{\alpha 6}$	X				X	X	X	X		X
$PSS_{\alpha 7}$	X			X	X	X	X	X		X

Based on the results of the case study for Company α, the following conclusions were derived:

- Most of the improvement scenarios are related to the maintenance cost and downtime of an elevator and can be tapped by all PSS options. A PSS option whereby the elevator itself is included in the 'per travel cycle' or 'per month' offering ($PSS_{\alpha 1}$) does not promise to have a significantly larger innovation potential than a PSS with a combined input-based elevator offering and AB or UB maintenance and spare parts offering. Only $A9$ can be tapped additionally by $PSS_{\alpha 1}$. Because $PSS_{\alpha 1}$ would require that the initial investment in the elevator is done by Company α, this model encompasses important risks for Company α and the potential rewards were not considered to be sufficient. Incorporating a cleaning service in the offering was not considered practically realizable by Company α representatives, despite the significant improvement potential of scenario $A9$.

- Both $PSS_{\alpha 2}$ and $PSS_{\alpha 3}$ represent a potential to reduce the maintenance cost on average with 48,5% (calculated by combining the improvement potential of scenarios $A1$, $A5$, $A6$, $A7$ and $A8$[3]). The difference between both PSS models is that the 'per travel cycle' model $PSS_{\alpha 2}$ offers more incentives for Company α to reduce planned and unplanned downtime, since that would allow to increase the number of travel cycles[4] and Company α's revenue, while in the 'per month' model $PSS_{\alpha 3}$ the revenues

[3]This cannot be done just by adding the potentials presented in Table 8.4, because they are mutually dependent. The average reduction was determined by first reducing the maintenance cost with the technical parameter changes and subsequently calculating the reduction of the logistical measures $A6$ and $A7$.

[4]This reasoning is only valid if the number of travel cycles is reduced in case the elevator is not operational. This reduction is only possible if some people take the stairways instead

of Company α are independent of the usage intensity. The choice between these two PSS-models should also take into account the other mechanisms that determine the business potential of a PSS, namely their ability to increase the customer base and to change the competitive environment (cfr. Section 3.4.1). Both models could be chosen and applied for different customer segments (e.g. 'per travel cycle' model for high use elevators and 'per month' model for low use elevators) or they could even co-exist (if maintenance and spare parts are charged at a fixed sum per month plus an extra rate per travel cycle above a certain treshold).

- The improvement scenarios related to the energy costs (A2 and A4) require investments with a discounted payback period that the project team considered too long and potential rewards that are too small in absolute value to compensate for the risks (e.g. customer insolvency). Therefore, including the energy cost in Company α's offering was not seen as especially promising.

- According to the information on which the simulation model was based, most of the (corrective and preventive) maintenance and spare parts costs are not driven by the number of travel cycles (except for FM15, cable replacement at the EOL) but by the elapsed time period. Therefore, for a 'per travel cycle' model (e.g. $PSS_{\alpha 2}$) the price per travel cycle should be high enough to account for the risk of a low usage intensity. For low or medium use elevators, a per travel cycle model might even be too risky for Company α. On the other hand, through Mechanism 4 of Section 3.4.1, a 'per travel cycle' model might be able to attract more customers into accepting a maintenance contract. A possible adaptation to PSS option $PSS_{\alpha 2}$ to reduce the risks for Company α is that the customer pays a fixed sum per year for the integrated package of maintenance and spare parts, plus a surplus per travel cycle, if the number of travel cycles reaches a certain treshold. In any way, if a price for maintenance per travel cycle is determined, the number of floors in the building and the distance to the customer should be taken into account and not only the usage intensity. For this purpose, Equation 8.1 could be used as a first estimate, but the link between the failure rate and the number of travel cycles should be clarified through the collection of usage data, such that a more reliable linear approximation of the cost per travel cycle can be derived.

of using the elevator or if other elevators in the building transport more passengers per travel cycle due to the elevator's downtime.

Generic conclusions

The following *generic conclusions* can be derived from application of the methodology of Chapter 7 for Case α:

- This case confirms that a stochastic approach to quantify cost and value is necessary and useful, which was confirmed by Company α representatives. The many input uncertainties, for example with regards to the failure rates, number of travel cycles, number of floors and distance to the customer, have a fundamental impact on the uncertainty of the outputs (e.g. cost and downtime). A deterministic approach would not be able to take account of the influence of these various parameters.

- For the determination of the maintenance costs, the main information sources were expert opinions, since there were no reliable historical data available on which estimates for failure rates and failure impacts could be based. However, the desired accuracy for these costs could be achieved, which was confirmed by Company α representatives. Validation of estimates from independent sources was identified as critical. Thus, this case demonstrates that even if historical data are not available, useful estimates can be derived.

- During this case study, much was learned with regards to how the results of the output analysis are to be shown for optimal intelligibility. Especially the representation of results in Figures 8.3 and 8.6 was deemed insightful by company representatives.

- In Case α, estimates for certain critical parameters could only be derived based on information from (potential) customers. For example, the number of travel cycles per elevator in a hospital and the number and duration of cleaning activities for an elevator in a hospital could only be determined based on historical data and external estimates.

- Case α demonstrates the application of Value quantification strategy 1 of Section 7.3, i.e. the determination of absolute value as a set of non-monetary performance indicators. The fact that the expression of value in monetary terms and thus that the extension towards Value quantification strategy 2 was not expected to lead to additional insights, was based on two factors: on the one hand the large customer-specificity of the maximum WTP for the improvement of a performance indicator[5], and on the other hand the expectation that the actual WTP is significantly lower

[5] For example, the maximum WTP and thus the economic impact of an additional hour of uptime depends very much on the particular use situation of an elevator, even within one building.

than the maximum WTP for most performance indicators[6]. Although value was expressed as a set of non-monetary performance indicators, this approach was perceived as useful by Company α representatives.

- The quantitative approach that was followed in this case allowed to identify a broad set of improvement scenarios that have a large impact on cost or on particular value aspects. Before the quantitative case was started for Company α, a brainstorming session was organized, whereby the central project team of Company α listed ideas, related to changes in the service delivery or in the product design, that would allow to reduce cost or increase value. In total, during a four hour session, 43 'service ideas' were identified and 25 'product ideas'. When these ideas are compared to the improvement scenarios of Table 8.3, only scenarios $A3$, $A7$ and $A9$ were identified during that session. The relative impact of these scenarios was not known at that moment, as for example the cleaning costs were initially underestimated. The fact that the presented approach allows to identify the scenarios that have the main impact on cost and value was deemed useful.

[6] For example, it was not considered likely that for a reduction of traveling and waiting time of the hospital personnel, the technical department of a hospital would be willing to pay a price that is close to the actual labor costs savings.

8.2 Case β: Lighting control systems

In this section[7], first some background is presented on lighting and lighting control systems, in Section 8.2.1. Subsequently, the four steps of the methodology of Chapter 7 are discussed in Sections 8.2.2 to 8.2.5.

8.2.1 Background: Lighting (control) systems

Articial lighting is responsible for between 20 to 45% of the total electricity demand in commercial buildings [57, 162]. A reduction of the energy consumption can be realized through the implementation of a diverse set of measures, including on the one hand the replacement of lighting systems (luminaires, lamps and ballasts) by the best available technology, and on the other hand the implementation of lighting control systems (LCSs), that allow to dim or switch off light sources based on the actual lighting demand.

Company β is a provider of LCSs and currently has a project-based business model. It implements LCSs based on the customer's specifications at a certain price per node, that includes all labor related costs and ownership transfer of all the LCS's components. The actual installation work is done by an electrical installation company. In many cases, the building owner is not a direct customer of Company β, but the electrical installation company is an intermediary in β's distribution channel towards the end user.

The LCS provided by Company β has the following characteristics:

- It consists of control units, daylight sensors, movement sensors and input/output modules. A user interface can be installed on personal computers.
- There are two possible communication protocols with the luminaires, of which – in order to limit the complexity of the analysis – we will only consider the DALI[8] protocol, whereby in each luminaire an electronic ballast is present that can communicate and be controlled individually by the LCS's control unit. Each control unit is typically connected with 300 to 500 nodes (luminaires).

[7]This chapter is partially based on a master thesis project at the KU Leuven Master of engineering program [223], in which a simulation model was developed for the value and cost analysis of the 'old offices' subsegment (cfr. infra). For confidentiality reasons, most of the monetary values of the cost analysis for 'recent offices' are multiplied with an unspecified scale factor.

[8]Digital Addressable Lighting Interface (DALI) was defined by Annex E.4 of IEC 60929 [89] as a digital signal controller for control interface ballasts and modified by IEC 62386 [90].

- In the LCS, different strategies for reducing the lighting energy consumption are applied:
  - According to *time control*, a calendar is programmed that allows to dim or switch off lights at certain moments of the day/night.
  - In spaces where movement detectors are installed, *occupancy control* can be applied – i.e. the lights can be dimmed or switched off if nobody is present in that room.
  - In spaces that are (partially) illuminated by ambient natural light, *daylight control* can be applied to dim the lamps in relation to incoming light level.
  - The illuminance of a task area will reduce over the maintenance cycle of a lighting system due to pollution and ageing of the installation and room surfaces. This is expressed by a *maintenance factor* MF, which is defined as the ratio of the illuminance E_{end} of a given surface at the end of the maintenance cycle over the initial illuminance E_{init} of the same surface [174]. Therefore, if no lighting control is applied, the illuminance will be set above the prescribed levels in the beginning of the maintenance cycle to ensure that at its end the surface is still sufficiently illuminated. The lighting control strategy *constant illuminance control* dims the lamps such that the illuminance level is always constant at E_{end}.
  - In *personal control*, the user is allowed to regulate the illuminance of his or her individual office area through a personal user interface.

The main reason why Company β is interested in adopting a PSS is to increase its customer base by lowering investment barriers (i.e. through Mechanism 4 of Section 3.4.1)[9]. This could be achieved, for example, through the implementation of PSS options $PSS_{\beta 1}$ or $PSS_{\beta 2}$ (Cfr. Table 6.3), that are restricted to the implementation of an LCS and do not entail changes to the lighting system. Alternatively, the activities of Company β could be expanded such that, in addition to implementing LCSs, it replaces outdated lighting systems, according to PSS option $PSS_{\beta 4}$, and assumes full responsibility for managing the LCSs and the lighting systems in the customers' building. In each of the PSS options $PSS_{\beta 1}$, $PSS_{\beta 2}$ and $PSS_{\beta 4}$, the investments in the LCS and – optionally – the lighting system would be paid according to the actual savings in energy consumption (expressed in kWh) or in energy costs (expressed in €). Therefore,

[9] Another incentive for Company β to adopt a PSS is to change the competitive environment (Mechanism 3). Because currently the electrical installation companies are its customers, there is a disproportionate focus and pressure on prices instead of value and long term cost effectiveness of the end user's lighting system. By directly offering the end users a PSS, thus price pressure could be reduced.

it is essential for Company β to have a clear view on the cost to deliver such a PSS and on its value (which, as we will see, is mainly related to a reduction of lighting energy costs).

8.2.2 Step 1: Goal and scope definition

Customer segments

The customer segmentation basis chosen during discussions with the central project team is *application type*, according to which the following segments were identified:

- Office buildings
- Industrial buildings and warehouses
- Healthcare premises
- Car parks
- Sports halls

The segment that was identified as especially promising for a PSS model and for which a quantitative analysis was performed is ‘office buildings’, because of its market size. In principle, the central project team of Company β judged that a PSS model could be interesting for each of the aforementioned segments.

According to [222], the 25 EU member states (2007) represent a total office building stock of 840 km². The largest European countries by office area are presented in Figure 8.7 (derived from [222][10]).

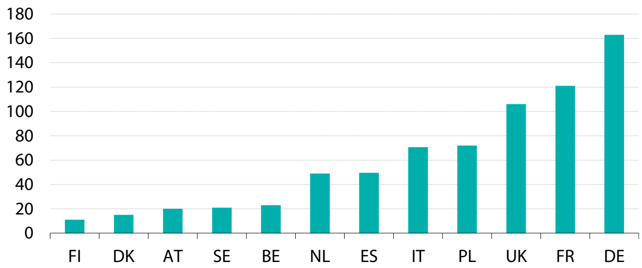

Figure 8.7: Total office floor area [km²] in selected European countries (derived from [222]). Country codes are according to ISO 3166–1.

[10] For calculating the office area in Italy and Spain, an average office floor area of 1,27 m² per inhabitant was assumed, as indicated in [222].

According to the type of lighting system present, ***two subsegments*** within the office buildings segment are discerned:

- The first subsegment includes office buildings whereby the lighting system is 'up-to-date' and allows for the direct implementation of an LCS. When this subsegment, which we will call ***recent offices***, is analyzed, we can focus on the impact of the LCS itself and will consider the lighting system as fixed. This subsegment is analyzed for the cost and value analysis of PSS options $PSS_{\beta 1}$, $PSS_{\beta 2}$ and $PSS_{\beta 3}$.
- The second subsegment includes office buildings with an outdated and energy-inefficient lighting system. For this subsegment, termed ***old offices***, a correct practice is to first renovate the lighting system itself and subsequently implement an LCS. This subsegment is included for the analysis of PSS option $PSS_{\beta 4}$.

Basis of evaluation

The functional results of an LCS correspond to those presented in the fourth column of Table 4.1, except for the solution-centric functional result, that can be formulated as follows: *'control the luminous flux in building A during one year'*.

In this case study, functional results on two levels of abstraction are particularly relevant:

- The solution-centric functional result (cfr. supra) is chosen as a evaluation basis for the analysis of the subsegment *recent offices*, since this only considers the LCS itself within the system boundaries.
- The environment-centric functional result (*'provide a guaranteed level of task area illuminance, expressed in lux, in building A during one year'*) is chosen as an evaluation basis for the analysis of the subsegment *old offices*. Now the lighting system itself (including luminaires, ballasts, lamps and wiring) falls within the system boundaries.

After discussions with Company β representatives, it became clear that a PSS whereby a promised level of visual comfort is to be delivered was not seen as a realistic option. The main difficulty was seen in the fact that visual comfort depends on subjective assessments [124]. Therefore, the demand-fulfillment result (i.e. provide a promised level of visual comfort) was not chosen as an evaluation basis.

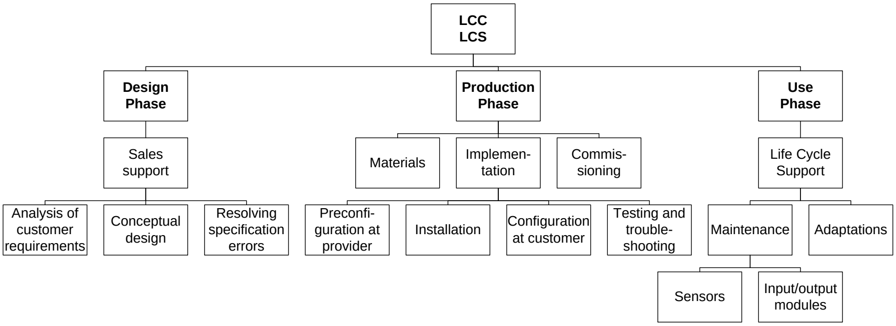

Figure 8.8: Cost Breakdown Structure for the analysis of recent offices for Case β.

System boundaries

The system boundaries are presented in Table C.1 of Appendix C. This table combines the system boundaries for both the old offices and the recent offices analysis. Each restriction was motivated by a need to control the complexity of the analysis and was deemed justifiable. For both analyses, the time horizon was chosen to be 20 years.

Cost components

The Cost Breakdown Structure for the recent offices segment is depicted in Figure 8.8. These are only the costs related to the LCS.

For the old offices segment, the Cost Breakdown Structure is depicted in Figure 8.9. Here, besides the cost components related to the LCS, all costs of the lighting system are included.

Value components

The main value components and performance indicators of an LCS[11] are presented in Table 8.6.

[11]This value decomposition only considers the LCS and not the lighting system itself.

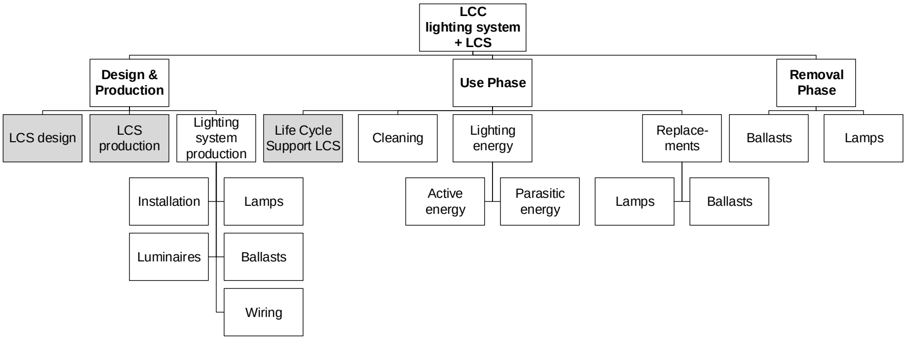

Figure 8.9: Cost Breakdown Structure for the analysis of old offices for Case β. Grey boxes refer to cost categories of Figure 8.8.

Table 8.6: Value components and corresponding performance indicators for Case β. The indicators displayed in bold were chosen for further analysis.

Value aspects	Value components	Performance indicators
Assurance	Conformity to norms and standards	• Conformity to standards w.r.t. illuminance of task areas (e.g. 'EN12464' [36]) [binary]
Convenience	Ergonomics	• Disturbing effects of lighting (e.g. reflections, blinding) [subjective scale]
Flexibility	Ability to cope with changing customer demands	• Time to perform adaptations to the LCS [minutes]
	Ability to facilitate external cost savings or revenue increase	• **Effect on lighting energy consumption, expressed as net discounted savings per surface area [€/m²] or as a discounted payback period [years]** • Effect on lamp replacement costs [€/m²]

8.2.3 Step 2: Model development

In this section, the model to quantify the cost and value per functional result for Case β is described. First, we do this for the subsegment 'recent offices' and subsequently, we highlight the main differences of the model structure for the subsegment 'old offices'.

Recent offices The outputs and main logic of the model can be described as follows:

- For recent offices, the *cost per functional result* represents the equivalent annual cost per node of an LCS, including on the one hand the initial labor related and material investment costs and on the other hand the costs for 'life cycle support' of the LCS (cfr. Figure 8.8). In particular, the initial labor related costs were subjected to a detailed analysis because they correspond to the main activities performed by Company β at this moment.

- For recent offices, the *value per functional result* was quantified according to Strategy 2 of Section 7.3.1, i.e. by expressing value in monetary terms as the maximum WTP. This maximum WTP corresponds to the main performance indicator of Table 8.6, namely the effect on the lighting energy cost. The maximum WTP is taken equal to the savings in comparison to a continued use of the same lighting system without an LCS. Value can be expressed as the NPV of these savings in €/m^2 or as the discounted payback period of the investment in an LCS, in years.

The structure of the simulation model for recent offices with input parameters in different categories is depicted in Figure 8.10.

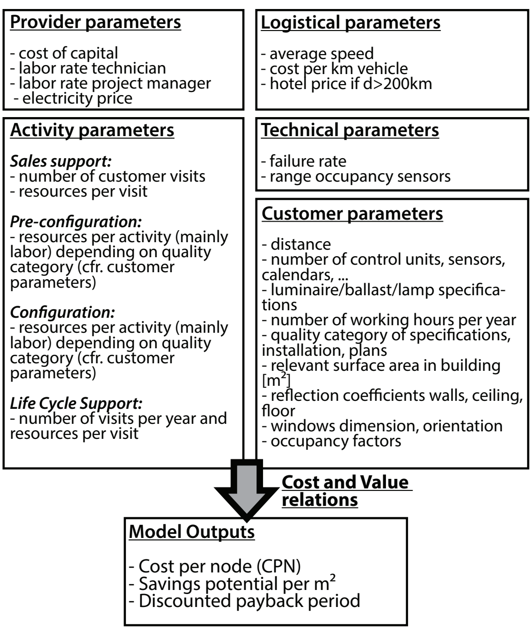

Figure 8.10: Model structure for Case β.

The *parametric cost relations* were determined as follows:

- The initial costs of implementing an LCS (design and production phase in Figure 8.8) were modeled by using time equations in a Time-Driven Activity Based Costing approach (cfr. Subsection 3.3.2). The resources consumed are mainly labor related, and for each type of employee involved (e.g. project manager, service engineer) the cost per minute was determined based on their wages, not taking into account overhead costs. To each activity, an appropriate activity driver was assigned. These activity drivers are mainly to be found in the customer parameters (cfr. Figure 8.10): the number of control units, daylight sensors, calendars to be programmed, etc.

- The time equations contain a conditional logic, because Company β representatives stated that the duration of each activity is influenced by three different *quality parameters*: the quality of specifications, the quality of installation work and the quality of building plans. Each of these quality parameters can be assigned to one of five categories (very bad, bad, average, good, very good). Some activities' durations depend mainly on the quality of specifications, some mainly on the quality of installation work, etc. Therefore, for each activity, the dominant quality parameter was indicated and the activity duration was estimated as a five point estimate (duration if the quality is very bad, duration if the quality is bad, etc.). An example for three activities is provided in Table C.2 of Appendix C.

For the value quantification, the potential lighting energy cost savings in a new lighting system due to the implementation of an LCS were calculated (in $^{€}/_{m^2}$). As demonstrated in [223], the savings in lamp replacement costs are negligible in comparison to the energy savings, and therefore their calculation method is not described here.

The energy savings were determined by an approach for which a more detailed description is provided in Appendix C. In summary, this approach determines the potential energy savings by applying formulas and parameter estimates provided in European standard 'EN15193' [35]. The potential energy savings are determined for four lighting control strategies:

- *Lighting control strategy 1*: application of time control and constant illuminance control
- *Lighting control strategy 2*: application of constant illuminance control and occupancy control

- *Lighting control strategy 3*: application of time control, constant illuminance control and daylight control.
- *Lighting control strategy 4*: application of constant illuminance control, daylight control and occupancy control.

Old offices

- For old offices, the *cost per functional result* of the integrated lighting and lighting control system represents all cost components of Figure 8.9 and is expressed in €/m^2.
- For old offices, the quantification of the *value per functional result* of the integrated lighting and lighting control system also follows Strategy 2 of Section 7.3.1. Value is expressed as the NPV of the resulting savings in €/m^2 or as a discounted payback period, whereby the comparison is made to the costs of the outdated lighting system.

Overall, a similar approach is followed in comparison to the recent offices analysis. The differences and specific assumptions for the old offices analysis are highlighted in Section C.2 of Appendix C.

8.2.4 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table C.3 of Appendix C, the main information sources used according to the four categories of Section 7.4.1 are listed. An important choice was made to base the value analysis mainly on literature sources. The limited availability of historical data for the actual energy consumption before and after implementation of an LCS necessitated this approach.

Uncertainties and risks

For Case β, scenarios were defined depending on the type of analysis performed:

- For the cost analysis of recent offices, the following parameters were used to discern scenarios: the project size (represented by the input parameter 'number of control units'), the distance to the customer ('0-200 km' versus '201-400 km'), the quality of specifications and installation work.

- For the value analysis of recent offices, four scenarios were defined according to the lighting control strategy applied (cfr. Section 8.2.3).
- For the cost analysis of old offices, scenarios were defined based on the type of office (landscape versus cellullar).
- For the value analysis of old offices, scenarios were defined based on the type of office, the type of lighting control strategy and the type of lamp-luminaire-ballast combination that represents the old lighting system (5 options were considered, cfr. Section 8.2.3).

The choice of the most important statistical distributions that represent the uncertainties in the input parameters is clarified in Table C.4 of Appendix C.

Output analysis and validation

Cost analysis for recent offices As mentioned in Section 8.2.3, the cost analysis for recent offices focused on the labor related costs in the design and production phase of an LCS. After the initial output analysis, derived from running a Monte Carlo simulation model with 5000 iterations, the following conclusions were derived:

- Although the initial work carried out by Company β to implement an LCS consists of 58 different activities, 76% of the labor related cost is determined by 16 activities and 50% of the cost by only 7 activities (cfr. Figure 8.11, another illustration of the Pareto principle). This gives Company β a clear idea which of the activities should be streamlined for cost optimization.

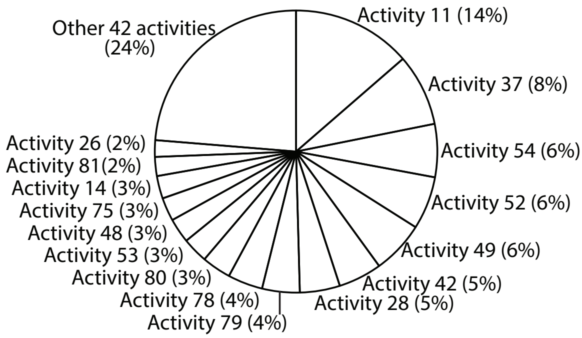

Figure 8.11: Average initial labor related costs of an LCS decomposed into the main activities (only of the design and production phase, cfr. Figure 8.8).

- The initial labor related cost per node of an LCS is highly dependent on the project size. As can be seen from Figure 8.12, small projects correspond to a significantly larger cost per node, while the difference between larger projects is not so distinct (e.g. five versus six control units) because certain activities are to be considered as a fixed cost per project (i.e. require labor inputs irrespective of the number of nodes) and the relative contribution of these activities to the total cost decreases for a higher number of control units. This indicates that if the price per node of the LCS is made independent on the project size, especially the profitability of small projects is not assured.

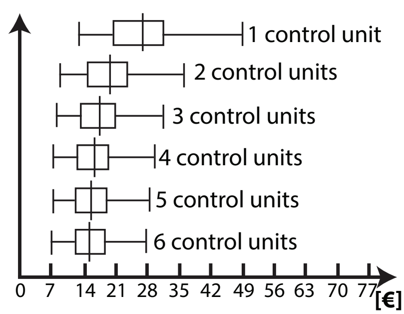

Figure 8.12: Initial labor related cost per node of an LCS (the same categories as in Figure 8.11) for six different scenarios corresponding to project size (i.e. number of central control units).

- The initial labor related cost per node of an LCS is highly dependent on the quality of the provided specifications (cfr. Figure 8.13). Especially bad and very bad specifications are costly, while the differences between normal, good and very good specifications are not so outspoken.

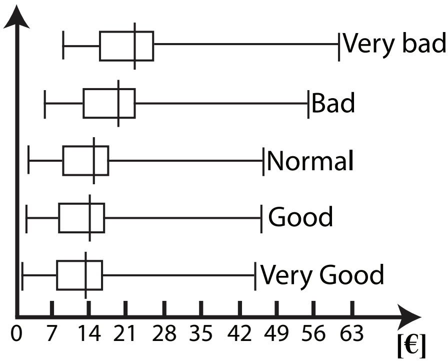

Figure 8.13: Initial labor related cost per node of an LCS for five different scenarios corresponding to the quality of the specifications.

Value analysis for recent offices The following results were obtained by analyzing the value of an LCS for recent offices:

- For the four lighting control strategies of Section 8.2.3, the relative energy savings were calculated in comparison to the situation where the same lighting system is used without automatic lighting control. First, the savings in energy consumption were analyzed (i.e. in [kWh], not in [€]). Boxplots are presented in Figure 8.14. As can be seen from this figure, the savings due to daylight control (in Strategy 3) are significantly more variable than those from occupancy control (in Strategy 2). Logically, Strategy 4, which combines occupancy, daylight and constant illuminance control, is expected to generate the largest savings, on average about 38%. When the savings potentials of Figure 8.14 are compared to values found in the relevant literature (especially the review of Dubois and Blomsterberg [57]), we notice that they fall within the ranges obtained, but are somewhat on the conservative side. Several reasons can be found for this:
  - The savings due to personal dimming (i.e. personal control, cfr. Section 8.2.1) are not included, because hardly any reliable estimates could be found. Based on experiments, Newsham states that the

expected additional potential of personal dimming can be up to 25% [152].

– Savings due to daylight control in particular are notably uncertain and difficult to forecast [25].

– In the experience of Company β representatives, an additional potential is expected from the fact that often lighting systems are imperfectly designed; excessive illuminance levels (i.e. 'over-lighting') are common. Apart from over-lighting due to the maintenance factor (cfr. Section 8.2.1), this is not taken into account here, as we assume that the lighting system is originally designed according to the relevant standards.

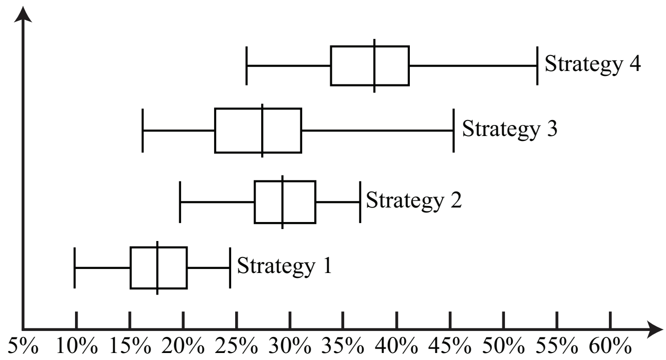

Figure 8.14: Boxplots of the energy savings [%] due to the implementation of an LCS in a recent landscape office, for the four lighting control strategies of Section 8.2.3.

- Figure 8.15 presents an overview on the sensitivity of the energy savings potential of the most advanced lighting control strategy (i.e. Strategy 4) as a function of selected input parameters. These input parameters indicate what the key factors are that drive the savings potential of Strategy 4 (i.e. the factors that determine that the savings potential is close to 50% instead of 25% in the upper box plot of Figure 8.14). The most important parameters are related to daylight control. Especially in offices that have a large daylight dependent part (which is the part of the office area in percentage that is illuminated by the sun coming through the windows, cfr. EN15193 [35]), a large savings potential exists. The room index RI is the second most important parameter for explaining the output variability –

it is determined as the ratio of the horizontal to the vertical surface area[12]. The main influence of the room index on the savings potential is also determined by daylight control and is related to the width of the office; the wider the office, the smaller the daylight dependent area and thus the smaller savings can be achieved through daylight control. The maintenance factor MF determines the savings potential due to constant illuminance control. It is mainly influenced by how often lamps, luminaires and the office surfaces are cleaned and maintained [222]. MF is defined as the product of luminaire maintenance factor (LMF), lamp maintenance factor (LLMF) and ballast maintenance factor (BMF). Figure 8.15 presents the ranking of these parameters by their contribution on the output variation. The abscence factor F_A influences the potential savings due to occupancy control: the more frequent offices are empty, the more the lights can be switched off. The numbers in Figure 8.15 indicate the corresponding input parameter values at the borders of the conditional averages interval. For example, for a daylight dependent part of 10%, the corresponding savings potential is 34% and for a daylight dependent part of 95%, on average about 50% of savings are possible. The vertical dotted line represents the average over all input parameter variations (it corresponds to the middle line in the upper boxplot of Figure 8.14).

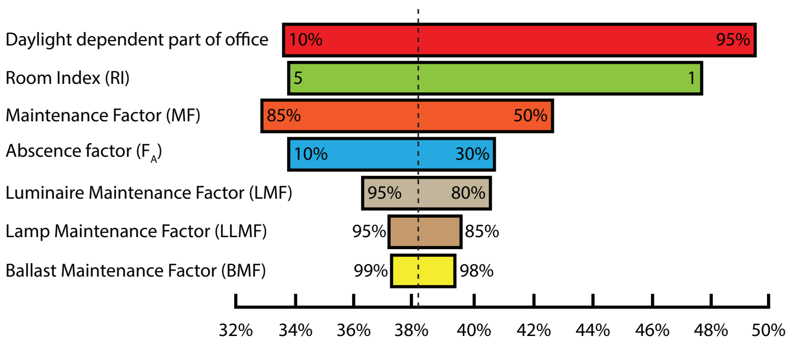

Figure 8.15: Tornado chart depicting the evolution of the average energy savings [%] due to Strategy 4, as a function of selected input parameter variations.

[12] $RI = \dfrac{L \cdot W}{(L+W) \cdot H}$, with L the length and W the width of the task area (i.e. the office) and H the height distance between the luminaire and the task area.

- Besides energy efficiency, two extra factors should be taken into account to assess the value of an LCS for recent offices: the initial investment and the electricity price. In Table 8.7, key results are given for the initial investment and various profitability measures of an LCS:
  - The *initial investment* I_0 is expressed in €/m² of illuminated office area.
  - The *Net Present Value (NPV)* of the LCS (in €/m²) is calculated over a period of 20 years, with a discount rate of 10%[13] and subtracts the initial investment from the discounted forecasted energy cost savings. Besides the average, 10^{th} and 90^{th} percentiles are given.
  - The *discounted payback period (DPB)* is related to the risk associated with the investment in an LCS. It represents the number of years it takes before I_0 is recuperated, if all saved energy costs are discounted with a discount rate of 10%.
  - The *payback period (PB)* is the same as DPB, but disregards discounting.
  - The *profitability index (PI)* indicates the net present profit obtained per unit of initial investment in the LCS.

The main conclusion that can be derived from Table 8.7 is that all lighting control strategies are profitable and that their ranking derived from Figure 8.14 is confirmed. Although Strategy 4 requires the largest initial investment, it is always superior to the other strategies according to each criterion (except I_0). Therefore, from now on we will only consider an LCS that works according to Strategy 4.

[13]An estimate for the WACC of Company β determined in consultation with company representatives.

Table 8.7: Value analysis of an LCS in a recent office, for four lighting control strategies, with selected performance indicators: Net Present Value (NPV), Discounted Payback Period (DPB), Payback Period (PB), Initial investment (I_0) and Profitability Index (PI).

		Lighting control strategies			
		Strategy 1	**Strategy 2**	**Strategy 3**	**Strategy 4**
I_0 [$€/m^2$]	average	3,6	5,1	4,9	6,4
NPV [$€/m^2$]	10%	0,1	1,5	1,2	2,3
	average	2,5	4,9	4,5	6,4
	90%	5,3	8,7	8,4	11,0
DPB [years]	10%	4,6	4,0	4,1	3,9
	average	10,1	7,2	7,4	6,6
	90%	18,0	11,1	11,6	10,2
PB [years]	average	5,6	4,7	4,8	4,5
$PI = {}^{NPV}/_{I_0}$ [%]	average	70%	96%	92%	101%

- A sensitivity analysis of the profitability potential of an LCS in a recent office was performed. Not surprisingly, by far the most important factor[14] that determines the discounted payback period (DPB) is the average electricity price. In Figure 8.16, a scatter plot is shown, whereby each marker represents one of the 5000 simulations and the black curve represents the evolution of the average DPB. As can be seen from this figure, the average DPB reduces from 10 years at 0.10 $€/kWh$ to 5 years at 0.20 $€/kWh$. For higher electricity prices, the DPB's variability is reduced as well. Figure 8.16 illustrates the profound impact of the electricity price on the value of an LCS. Electricity prices vary over time, and forecasting their future development is challenging. Nevertheless, in the report 'EU Energy trends to 2030 (update 2009)' published by the European Commission, future pre-tax electricity prices are forecasted, based on application of the PRIMES energy system model (cfr. Figure 8.17) [32, 63]. From the standpoint of Company β, rising electricity prices are beneficial as they increase the value of an LCS dramatically. Apart from their variability over time, electricity prices depend on the type of customer (i.e. the consumption band), since large industrial electricity consumers pay significantly less per kWh than small consumers. In Figure 8.17, the electricity price evolution for the service sector is closer to the prices for households than to that for industrial customers. Eurostat publishes historical electricity prices only for two categories, medium sized industrial customers and households. Since most offices are in the

[14] The rank order correlation (Spearman's ρ) between DPB and the electricity price is 0.766.

'Industry' and 'Services' segment of Figure 8.17, the electricity prices for both Eurostat categories are presented in Figures C.1 and C.2 in Appendix C, for selected (mainly Western-)European countries. From these figures, it is apparent that there is a significant geographical variability of electricity prices (with ranges from 0,08 to 0,20 €/kWh for industrial customers and from 0,15 to 0,30 €/kWh for households). For Company β, a geographically inspired business development strategy seems appropriate. This allows Company β to target customer subsegments where the value of an LCS is sufficiently high (i.e. above a certain NPV and/or below a certain DPB).

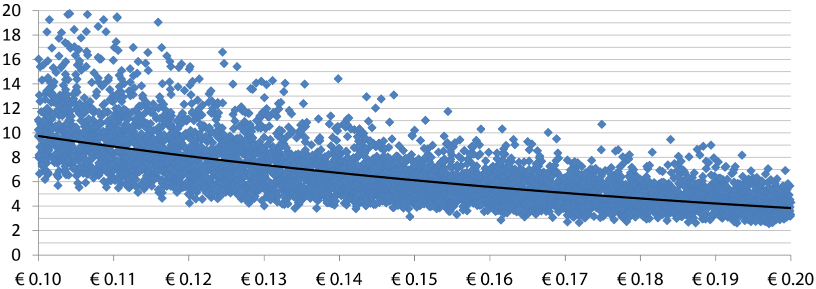

Figure 8.16: Scatter plot (5000 simulations) of the discounted payback period (i=10%) for the implementation of an LCS according to Strategy 4, as a function of the average electricity price in €/kWh.

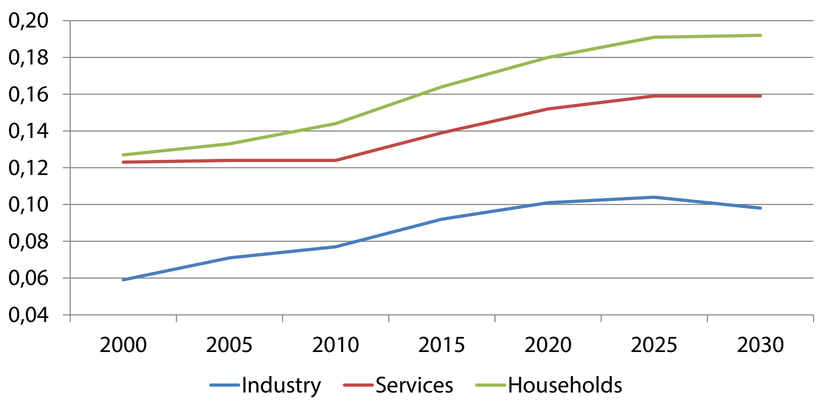

Figure 8.17: Forecasted average pre-tax electricity prices for the EU27 in €/kWh for industry, services and households, derived from the PRIMES energy system model [32, 63].

- To have a clearer view on how the value of an LCS for recent offices depends on other factors than the electricity price, a simulation was performed for one specific electricity price scenario derived from Figures 8.17 and C.2. An electricity price of 0,18 €/kWh in 2013 was assumed, with a linear increase of 33% up to 0,24 €/kWh in 2033. For this scenario, the average DPB is 4,6 years and the average NPV 10,7 €/m^2. The regular payback period is on average 3,5 years. For this electricity price scenario, a tornado chart depicting how the average DPB evolves with variable input parameters is presented in Figure 8.18. The maintenance factor of the lighting system is now the most important input parameter for explaining the variation in DPB. If we compare this figure to Figure 8.15, we see that the parameters related to daylight control lose importance versus those related to constant illuminance control. This is a result of the discounting included in the calculation of DPB. The savings due to constant illuminance control are maximal at the beginning of the maintenance cycle of the lighting system and therefore they 'carry more weight' in the cash flow calculation than the savings due to daylight control, that have a similar magnitude each year.

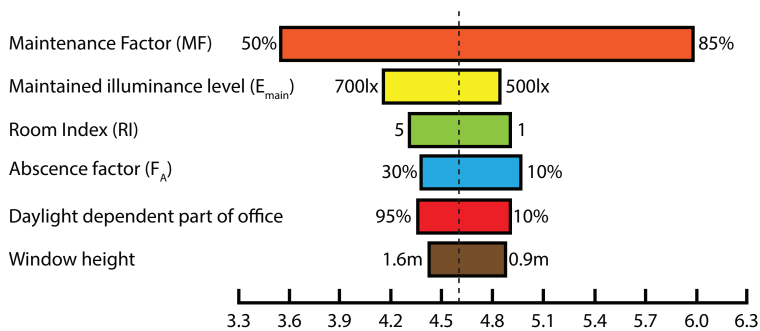

Figure 8.18: Tornado chart depicting the evolution of the average discounted payback period (DPB, in years) of an LCS (Strategy 4), as a function of selected input parameter variations, with a constant linear electricity price evolution.

Cost and value analysis for old offices The cost and value analysis for old offices is summarized in Section C.3 of Appendix C. The main conclusions from this analysis are that the LCS only accounts for a small part of the total cost of the integrated lighting system and lighting control system offering, but has, through Lighting control strategy 4, a positive effect on the value offered (i.e. NPV, DPB, PB and PI). However, the DPB is significantly longer than that for the recent offices analysis (about 15 years on average for landscape offices).

The key determinants of the profitability for the old offices segment are the electricity price, the room index and the characteristics of the original lighting system.

8.2.5 Step 4: Improvement scenario analysis

Identification of improvement scenarios

The improvement scenarios for Case β are briefly described in Table 8.8.

Table 8.8: The main improvement scenarios to reduce cost or improve value, identified within Case β.

Parameter category	Description of improvement scenario
customer parameters	*B1*: focus on specific subsegments within the *recent* offices subsegment, where the additional value of an LCS is maximal
	B2: focus on specific subsegments within the *old* offices subsegment, where the additional value of an LCS is maximal
	B3: differentiating the prices for initial implementation service based on project size and the distance between Company β and the customer's site.
activity parameters	*B4*: increasing the quality of specifications by streamlining the specifications elicitation phase with two categories (e.g. from very bad to normal, from normal to very good)
	B5: increasing the quality of installation by training installation personnel
	B6: increasing the time efficiency of activities 11, 37, 54, 52, 49, 42 and 28 with 50% (cfr. Figure 8.11)

Analysis of improvement scenarios

The results of the quantitative analysis of the improvement scenarios of Table 8.8 are summarized in Table 8.9.

Table 8.9: The main results of the quantitative analysis of the improvement scenario examples of Table 8.8.

Parameter category	**Main results of the quantitative analysis**
customer parameters	*B1*: As elaborated in Section 8.2.4, the profitability of implementing an LCS in a recent office depends on the *electricity price*, which is determined by the geographical location and consumption band of the (potential) customer; the *maintenance factor* of the lighting system, determined by the type of luminaire, lamp and ballast; the *room index*, *window height* and *daylight dependent part* of the office, which determine the savings from daylight control, and the *abscence factor*, that drives the savings from occupancy control. A detailed sensitivity analysis of the profitability as a function of the variation of these input parameters was performed. Company β should especially target customers in countries with a high electricity price (e.g. Germany, Italy), should focus on lighting systems with a low maintenance factor and buildings that catch a lot of sunlight. *B2*: As elaborated in Section 8.2.4 and [223], the profitability of implementing a new lighting system and an LCS in an 'old office' depends on the electricity price, the room index and the type of lighting system (luminaire-lamp-ballast combination) that characterizes the base case scenario. Cellullar offices are significantly less profitable than landscape offices. *B3*: A linear regression analysis of the average initial labor cost per node of an LCS as a function of the dominant input parameters suggests a 43,5% cost difference per node if the distance is larger than 200km and a 0,5% price difference per extra kilometer. Therefore, more competitive prices could be offered to customers closer to Company β's site. Projects with 1 and 2 control units are on average 75% and 28% more expensive per node than projects with 6 control units. Price differentiation based on project size could be considered.
activity parameters	*B4*: Increasing the quality of specifications from very bad to normal or from normal to very good leads to an initial labor cost saving of €4,4 and €1 per node respectively. *B5*: Increasing the quality of installation from very bad to normal or from normal to very good leads to an initial labor cost savings of €4,3 and €0,9 per node respectively. *B6*: Increasing the efficiency of the seven most important activities with 50% reduces the initial labor cost per node with 24%.

Conclusions for Case β

In Table 8.10, the improvement scenarios are linked to PSS options $PSS_{\beta 1}$ to $PSS_{\beta 4}$ (described in Table 6.3 and represented in Figure 6.3)).

Table 8.10: Matrix linking improvement scenarios $B1$ to $B6$ of Table 8.8 with the four PSS options for Company β.

	B1	**B2**	**B3**	**B4**	**B5**	**B6**
$PSS_{\beta 1}$	X		X	X	X	X
$PSS_{\beta 2}$	X		X	X	X	X
$PSS_{\beta 3}$			X	X	X	X
$PSS_{\beta 4}$		X	X	X	X	X

Based on the results of the case study for Company β, the following conclusions are derived:

- Improvement scenarios $B4$, $B5$ and $B6$ are related to efficiency improvements in the design and production phase of the LCS. These can be tapped in any PSS option whereby the implementation service is not sold according to a fully input-based revenue mechanism. Since in $PSS_{\beta 3}$, which corresponds to the current offering of Company β, a *fixed* price per node is charged, the realization of improvement scenarios $B4$, $B5$ and $B6$ will also result in a lower cost per node.
- To reduce the costs of the design and production of an LCS, it is essential for Company β to control the quality of specifications and of installation work, whereby the most is to be gained by improving the quality from 'very bad' to 'normal'. An improvement from 'normal' to 'very good' does not promise a large cost reduction (cfr. Table 8.9). Although the complete design and production phase of an LCS consists of 58 activities, streamlining 7 of these activities could already reduce the average cost per node with 24%.
- The distance to the customer and the project size have a major impact on the initial labor related cost per node of LCS. Especially in cases where the initial labor related cost is dominant (PSS options $PSS_{\beta 2}$ and $PSS_{\beta 3}$), Company β should consider increasing the price per node for small and long distance projects.
- PSS option $PSS_{\beta 1}$, i.e. the sales of an LCS in a recent office as an "energy savings service", charging the customer only the saved energy costs, is a profitable option for Company β in case the electricity cost is high

enough, for lighting systems with a low maintenance factor and for offices where the savings for daylight control are substantial (i.e. large windows, high daylight dependent area). Lighting control Strategy 4 (combination of constant illuminance, daylight and occupancy control) requires the largest initial investment but has the highest NPV and shortest DPB of all lighting control strategies. The average discounted payback period is 6,6 years (assuming a discounting rate of 10%). This discounted payback period will be indicative of the length of the contract with the customer and of how risky the project is. However, the following factors not taken into account in the model will influence this DPB in a positive way:

  - Subsidies and government support mechanisms for investments in energy efficiency (e.g. "green current certificates").
  - Potential larger savings due to personal control and due to 'overlighting' of the initial configuration at the customer.
  - If compared to the savings projected in other studies and in commercial case reports, the savings as calculated by EN15193 [35] appear to be on the conservative side. If more accurate historical data would become available on the actual savings realized in office buildings, the model parameters could be adjusted.

- PSS option $PSS_{\beta 4}$, i.e. the implementation of a new lighting and lighting control system in an office with an outdated, energy inefficient lighting system as a service, whereby the customer only pays the saved energy costs, is on average profitable over a period of 20 years in landscape offices. However, the DPB is on average 15,2 years with an LCS operating according to Strategy 4. The LCS has a positive effect on the DPB and NPV of this option over manual control. Its contribution to the initial investment is limited: the costs for luminaires and cabling are dominant. The long DPB, large initial investment and lower NPV per m^2 makes this PSS option less interesting than $PSS_{\beta 1}$ from Company β's perspective. The determining factors are electricity price, room index and lamp-luminaire ballast combination of the current lighting system.

- Due to the large geographical variability of electricity prices in the European market, in any case Company β should focus on countries where the value of an LCS is maximal due to high electricity prices. Customers in low consumption bands in countries such as Germany and Italy already pay around 0,25 $^{€}/_{kWh}$ (cfr. Figure C.2), represent a significant office building stock (cfr. Figure 8.7) and therefore should be primarily targeted.

- Company β representatives pointed out that the main business potential of $PSS_{\beta 1}$, $PSS_{\beta 2}$ and $PSS_{\beta 4}$ resides in the ability of these models to attract extra customers for which the investment threshold associated with option

$PSS_{\beta 3}$ is too high (thus, Mechanism 4, 'increase customer base', is crucial). Quantifying reliably how many extra customers these PSS options might attract was deemed infeasible without actually implementing this PSS in practice. Since in option $PSS_{\beta 2}$ the material investments at the start of the project are borne by the customer, the investment threshold is higher but the risks for Company β are lower. This option could be seen as an intermediate form of options $PSS_{\beta 1}$ and $PSS_{\beta 3}$ and, if properly designed, could combine advantages of both options: a reasonable risk level for Company β and an expanded customer base.

Generic conclusions

The following *generic conclusions* can be derived from application of the methodology of Chapter 7 for Case β:

- This case illustrates how the value of an investment good can be analyzed in a systematic way according to Value quantification strategy 2. The applicability of this strategy is related to the fact that the main value of this investment good lies in a reduction of costs. Moreover, an illustration is provided of how even in cases where not enough reliable historical data are available to derive value estimates, approaches in literature sources or technical standards can be applied for this purpose.

- The introduction of quality factors in the cost model allows to identify the cost potential of increasing the quality of factors such as specifications, installation work and construction plans. The fact that the presented approach allows to calculate a budget per node for the improvement of these quality factors was perceived as particularly useful by Company β representatives.

- The approach consisting of a combination of TD–ABC and LCC was judged as suitable to derive the general structure of the cost model, especially given the fact that most parameters in the simulation model were activity parameters.

- As Case α, this case confirms that a stochastic approach to quantify the cost improvement potential of a PSS is necessary. Insights on the dependency of the cost on parameters such as the quality of specifications, the project size and the distance to the customer were identified as the main outcomes of the cost analysis.

- This case is an example of an investment good for which the value is mainly situated in a reduction of the energy costs. The complementary approach applied for modeling the electricity price (as a distribution or by assuming a fixed linear evolution) allows to obtain both detailed insights on the influence of the electricity price and on that of other input parameters and is advisable in similar cases.

- In this case study, the key parameters that drive the value of the LCS are customer-specific and not parameters that are under direct control of the provider. Therefore, this case illustrates primarily how interesting customer subsegments can be identified for which the value of an investment good is maximal. Before the quantitative analysis was performed, Company β representatives only indicated that the maintenance factor was a major determinant of the LCS's value, while other influential parameters (cfr. Figure 8.18) were not known.

- Case β illustrates that key profitability factors can differ significantly between various PSS options. In the least performance based PSS, $PSS_{\beta 3}$, whereby Company β would be paid a fixed price per node for the implementation of an LCS, a reduction of the labor related costs is the main priority to increase the profitability. The main focus of Company β should be on improving the service delivery efficiency for a selected set of activities (cfr. Figure 8.11). Moreover, a price differentiation based on distance and project size is advisable. If the labor related implementation costs are charged based on a percentage of the energy costs saved ($PSS_{\beta 2}$), and certainly in the more integrated PSS option ($PSS_{\beta 1}$), the focus of Company β shifts towards matching its business development strategy with the main factors that drive the value of the LCS. The value of the LCS is more variable than its cost and therefore knowing the customers where the LCS's value is high becomes more important than service delivery efficiency. If the LCS is further integrated with a lighting system, in option $PSS_{\beta 4}$, the profitability indicators change (cfr. Appendix C). Now, for example, the characteristics of the original lamp-luminaire-ballast combination determines the potential savings. Furthermore, the time horizon in $PSS_{\beta 4}$ is significantly extended. Remarkably, the influence of one profitability indicator (the room index) is even reversed if we compare $PSS_{\beta 1}$ with $PSS_{\beta 4}$. For recent offices, a small room index is always preferred, due to its positive impact on the daylight control savings, that result in a shorter DPB. For old offices, the relation between DPB and room index is more complex: a smaller room index corresponds to a larger initial investment in the lighting system and therefore if the room index RI is between 1 and 2, the DPB is longer than if $RI > 2$. Thus, Case β illustrates how, depending on the type of PSS, other customer segments can emerge as the ones with the highest potential for profitability.

8.3 Case γ: Fire detection systems

This section covers a case study performed for Company γ, a provider of fire safety systems, introduced in Chapter 2. In Section 8.3.1, some background is presented on fire safety, detection systems and on the main reasons for Company γ to consider a PSS. In Sections 8.3.2 to 8.3.5, the four steps of the methodology are discussed.

8.3.1 Background: Fire safety and detection systems

Every year fires in buildings cause casualties, injuries and damage to property. The overall objective of fire safety engineering is to limit the total cost of fire to society [24]. This total cost can be divided into the following categories: direct and indirect fire losses, fire insurance, fire fighting organizations and fire prevention and protection [79]. The Geneva association collects international fire statistics and expresses them for different countries as a percentage of GDP. Some of the most recent available figures for Belgium and its neighbouring countries are presented in Figure 8.19 [73][16].

Requirements with regards to the fire safety of buildings are set by governments, fire fighting organizations and fire insurance companies. Overall, there is a worldwide trend towards the implementation of *performance based fire protection* of buildings [4, 24]. In performance based fire safety regulations, as opposed to traditional, prescriptive ones, no specific technical solutions are prescribed, but performance requirements are stated, e.g. on the maximum evacuation time in case a certain fire scenario occurs. This gives fire safety engineers and building designers more degrees of freedom in coming up with an optimal solution to protect a specific building.

Fire detection systems are one possible technology to achieve fire protection. They have three main functions: detecting a fire once it occurs, notifying building occupants of the emergency and informing fire fighting organizations about the location and the characteristics of the fire (cfr. Figure A.5). Current

For confidentiality reasons, most of the numerical values presented in this section are expressed relatively or, if monetary values are provided, they were multiplied with an unspecified scale factor.

[16] Comparison between data for different countries should be made with great caution. The provision of fire related statistics is voluntary and does not follow an internationally agreed methodology [237]. The oldest statistics refer to 2000 (e.g. fire insurance for Belgium), while the newest refer to 2009 (e.g. yearly fatal casualties for the Netherlands). For certain countries, certain statistics are not available (e.g. fire insurance for Germany).

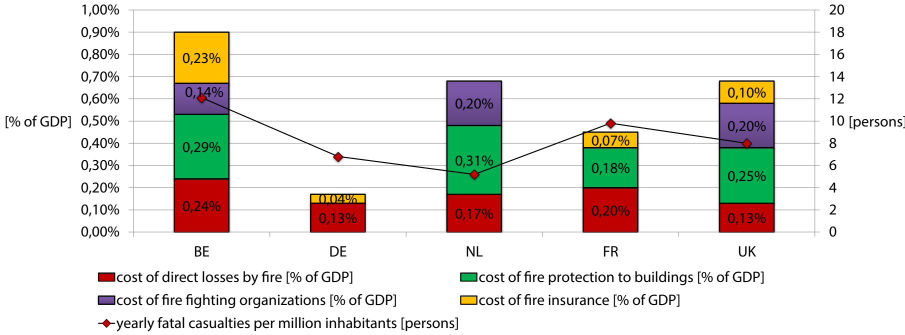

Figure 8.19: Statistics related to the number of casualties and various costs of fires in Belgium and neighbouring countries (source: Geneva Association World Fire Statistics Bulletin [73]).

detection systems respond to smoke, heat, gaseous emission or electromagnetic radiation generated during smoldering and flaming combustion [96]. The most commonly used type consists of *photoelectric spot detectors*, that are mounted to a ceiling or wall and that detect smoke particles at a single point [54].

Company γ is a provider and integrator of various fire safety systems, including detection systems, passive construction elements and fire extinguishing equipment. It is active in a highly fragmented market, whereby a typical decision and sales process involves many stakeholders (e.g. engineering specialists, architects, contractors, installation companies). The main reasons for Company γ to consider a PSS are the following:

- to reduce price based competition in the various markets it is operating. Decision makers at the demand side often choose the fire safety system that fulfills all minimum technical requirements set by the various stakeholders at the lowest possible initial investment cost. The 'big picture' (e.g. total cost of fire, life cycle cost of a fire safety system) is most often not taken into account in the current, project-based sales process.

- to be able to tap the potential of optimizing fire safety systems over their lifecycle, taking into account both the initial implementation and the 'in service' costs.

- to strengthen the competitive advantage that is offered by Company γ's large installed base. For example, Company γ aims to retain customers that have an outdated fire safety system that should be renovated in the coming years.

8.3.2 Step 1: Goal and scope definition

Customer segments

The customer segmentation basis chosen during discussions with the central project team of Company γ is *the applicable fire safety standards*, according to which the following segments were identified:

- Office buildings
- Industrial buildings and warehouses
- Healthcare premises
- Tunnels and infrastructure
- Retail

The segment that was identified as especially promising for a PSS model and for which a quantitative analysis was performed is 'Office buildings', because of its market size and the large size of individual customers.

Basis of evaluation

The functional results of a fire detection system (FDS) correspond to those presented in the fifth column of Table 4.1. After discussions with the central project team of Company γ, it was decided to take the solution-centric functional result (*provide fire detection in building A during one year*) as an evaluation basis, because of the company's experience and competences with FDS. This allowed on the one hand to control the complexity of the assessment, whereby other factors related to fire safety of the Functional Hierarchy Model (e.g. emergency lighting, fire insurance, fire extinguishing, cfr. Figure A.5) are not taken into account in the cost assessment. On the other hand, the prevailing fire safety standards and prescriptions of fire insurance companies in Belgium are still mostly solution-centric and thus a PSS whereby a provider promises an FDS conforming to these standards and prescriptions was deemed more realistic than a PSS whereby conformity to environment-centric performance indicators is promised.

System boundaries

The system boundaries are presented in Table D.1 of Appendix D.

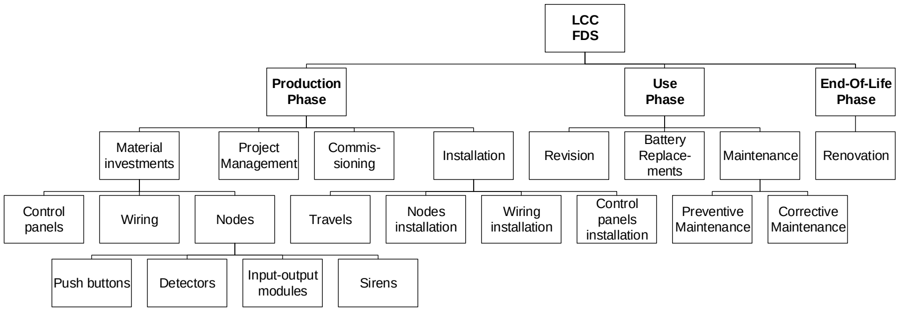

Figure 8.20: Cost Breakdown Structure for Case γ.

Cost components

The Cost Breakdown Structure is depicted in Figure 8.20.

Value components

The main value components and performance indicators of an FDS are presented in Table 8.11.

8.3.3 Step 2: Model development

The main focus in this case study is on the quantification of the cost reduction potential of a PSS. A model was constructed with as main output the cost per functional result, i.e. the equivalent annual cost per node[17], per detector and per m^2 of office area of an FDS, including all cost components indicated in Figure 8.20. The main complexity that had to be dealt with in the cost assessment is that an FDS can be highly customized, consisting of many different components in a variety of combinations.

The value of an FDS was analyzed by considering the performance indicators indicated in bold in Table 8.11. The main value quantification strategy followed is Strategy 1 of Section 7.3.1, i.e. the expression of value as a multidimensional set of mostly non-monetary performance indicators. However, as we will see, due to the difficulty in deriving reliable estimates for the main indicators, a detailed value quantification of an FDS was not achieved.

[17] A node of an FDS is a detector, an input/output-module, a siren or a push button.

Table 8.11: Value components and corresponding performance indicators for Case γ, organized according to the typology of value aspects listed in Section 7.2.5. The indicators displayed in bold were chosen for further analysis.

Value aspects	Value components	Performance indicators
Assurance	Conformity to norms and standards	• Conformity to fire safety standard NBN S21-100 [binary] • Conformity to fire insurers' prescriptions [binary] • Conformity to fire department's requirements [binary]
Responsiveness	Responsiveness to emergencies	• Intervention time in case of fire [hours]
Safety	Impact on fire safety risks	• **Effect on probability of (non-)fatal casualties in case of fire [%]** • **Effect on property damage impact of fire [€]**
Flexibility	Ability to facilitate external cost savings	• **Effect on fire insurance tariffs [€]**
Productivity	Reliability	• Functional effectiveness in certain fire scenarios [%] • Number of node failures [number] • Number of false alarms [number]

The structure of the simulation model with input parameters in different categories is depicted in Figure 8.21.

8.3.4 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table D.2 of Appendix D, the main information sources for Case γ are listed.

Uncertainties and risks

All uncertain input parameters were modeled as distributions. Some notable choices are explained in Table D.3 of Appendix D. An important choice that had to be made was the determination of the customer parameters (e.g. number of detectors, sirens, push buttons, ...). Company γ representatives stated that in principle any combination of components could be possible. However, based on recorded data of previous projects, certain ranges of these parameters could

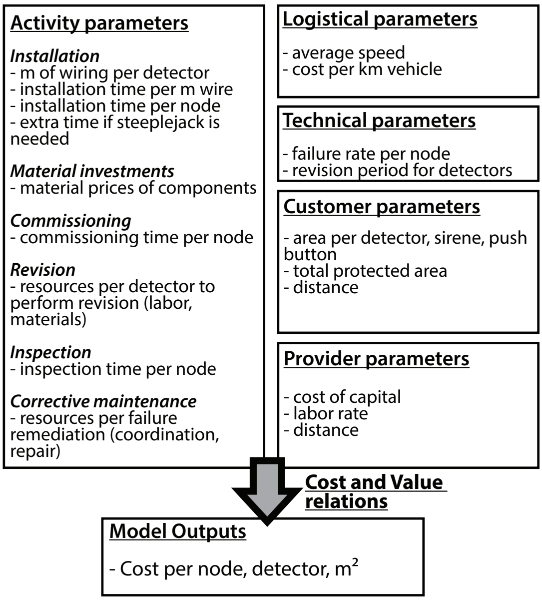

Figure 8.21: Model structure for Case γ.

be chosen that were deemed representative for the most common projects. For validation purposes, as will be clarified later in this section, scenarios were identified that allowed to compare the model outputs with recorded data in the company's accounting system.

Output analysis and validation

Cost analysis The distribution of the equivalent annual cost of an FDS were determined through Monte Carlo Simulation (5000 iterations). The following conclusions were obtained:

- The main cost categories are depicted in Figure 8.22, expressed as the equivalent annual cost with a discount rate of 10% (representing the weighted average cost of capital for Company γ). Since the cost category 'revision detectors' is only related to detectors, it is expressed as a cost per detector (CPD) instead of a cost per node (CPN). The initial installation cost is the single most variable cost component, while the material investment cost (which includes only the initial investment in the new FDS) is on average the largest. The costs were distinguished in two main categories for the analysis of the improvement scenarios (cfr. Section 8.3.5): initial costs (including installation, commissioning and material investments) and 'in service' costs (revision, corrective and preventive maintenance).

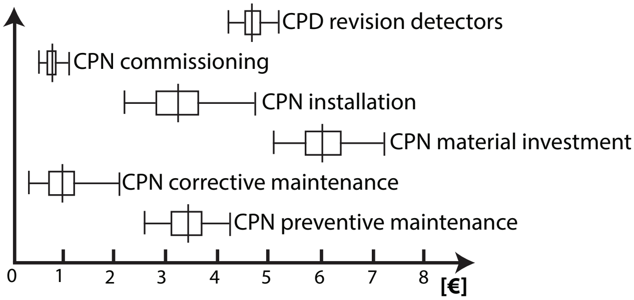

Figure 8.22: Equivalent annual cost per node (CPN) or per detector (CPD) for the main cost categories related to a fire detection system in an office building.

- A sensitivity analysis of the equivalent annual cost per node (CPN) was performed. A tornado chart depicting the evolution of the conditional average equivalent annual cost per node (CPN) of an FDS in an office building as a function of input parameter variations is provided in Figure 8.23. This chart lists the input parameters ordered by their impact on the CPN variation. Similar charts were drawn for the cost per detector (CPD) and the cost per m² (CPM²). In these charts, all dominant parameters are related to the number of components in the FDS design (e.g. area per detector, per siren, number of detectors per control panel).

- The initial investment in an FDS, broken down into cost categories, is presented in Figure 8.24 (10^{th} percentile, average and 90^{th} percentile). The categories *materials nodes*, *panels* and *cables* are determined by the applicable fire safety standards. From the sum of the averages of these 3 categories, the variation is –25% (10^{th}) up to +27% (90^{th}). Apart from negotiating lower component prices, these costs cannot be optimized, as the FDS is designed to comply the Belgian standard NBN S21-100, and thereby the number of different components is defined. A large share of the variability of the total investment per node is explained by the wiring installation costs (that vary almost ±50% from the average) and the logistical costs. The share of labor related costs in the total cost increases from 33% (for the 10^{th} percentile) to 38% (for the average) to 41% (for the 90^{th} percentile).

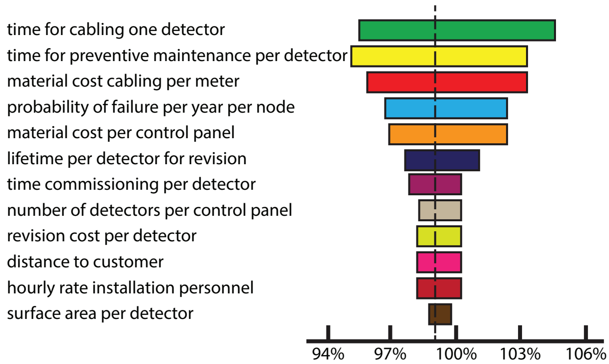

Figure 8.23: Tornado chart depicting the evolution of the total conditional average annual equivalent cost per node (CPN) of an FDS in an office building as a function of input parameter variations.

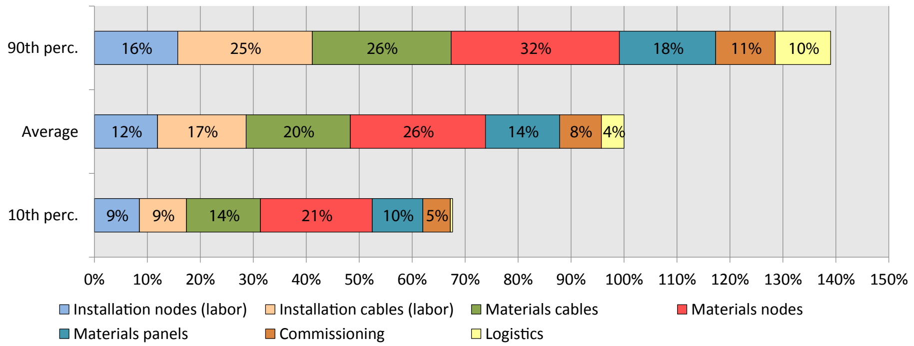

Figure 8.24: Decomposition of the total initial investment in an FDS per node (10^{th} percentile, average and 90^{th} percentile) into the underlying cost categories. The average investment per node is chosen as reference (i.e. 100 %).

- The LCC (including initial and 'in service' costs) and the 'in service' cost (ISC) of an LCS can be assigned to different cost objects: to one detector (CPD), to one m² of office area (CPM²) or to one node (CPN). If an FDS is sold in an integrated PSS, one of these objects can be chosen as a unit of pricing. The question can be raised which unit Company γ should prefer. The risk of a non-profitable contract is reduced if the variability of the unit cost is minimal. In Figure 8.25, the probability density functions (pdfs) of the CPD, CPM² and CPN are presented of the ISC and in Figure 8.26 of the LCC, whereby each distribution is 'normalized' by dividing it by its respective averages. As can be seen from these figures, for the ISC, all services related to an FDS can be sold according to a *price per node* or *per detector*, as the variabilities of both distributions are comparable. Selling an FDS per m² does not appear to be a good idea, since the variability of the CPM² distribution is considerably larger than that of CPD and CPN, depending mainly on the number of detectors per m² of office area, which is in its turn determined by the applicable technical standards. If an FDS is sold as a fully integrated package, including initial and in-service costs, there is however a significant difference in the variability of CPN and CPD. In Table 8.12, the standard deviation of all distributions of Figures 8.25 and 8.26 are presented, as well as the probability that the cost is more than 10% larger than the average. If the initial investment is included in the offering, a price per node is preferable over a price per detector.

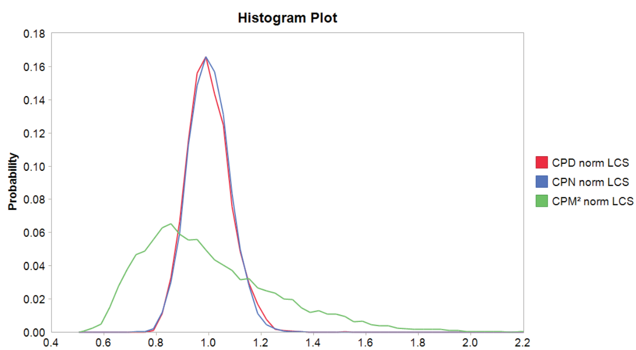

Figure 8.25: Probability density functions of the *'in service' cost (ISC)* per detector (CPD), per m² (CPM²) and per node (CPN), divided by their respective averages (5000 iterations).

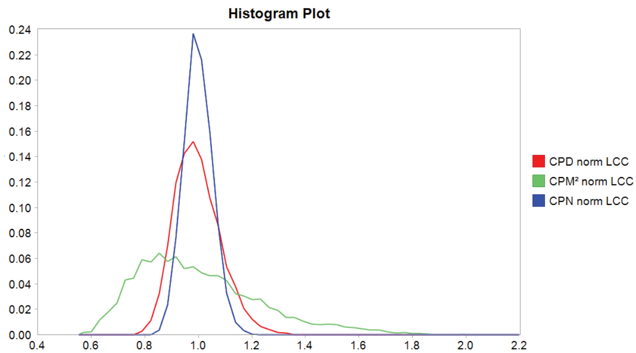

Figure 8.26: Probability density functions of the *life cycle cost* per detector (CPD), per m² (CPM²) and per node (CPN) divided by their respective averages (5000 iterations).

Table 8.12: Standard deviation of the 'normalized' life cycle cost (LCC) and in-service cost (ISC) per detector, m² and node and the probability that each of these variables is more than 10% higher than its average.

	$\sigma(LCC_{norm})$	$P(LCC_{norm} > 1,1 \cdot LCC_{norm}^{average})$	$\sigma(ISC_{norm})$	$P(ISC_{norm} > 1,1 \cdot ISC_{norm}^{average})$
CPD	0,0859	12%	0,0817	10%
CPM²	0,233	29%	0,259	30%
CPN	0,0531	3%	0,0786	10%

Validation of the cost model For *validation* of the model, the number of various components for fifteen recent projects carried out by Company γ were inserted in the model and the results of the cost related outputs were compared with the recorded costs in the company's accounting system. The main conclusions from this verification were that the results of the simulation model were in line with the data for the use phase (activity groups preventive and corrective maintenance, inspection, battery replacements and logistical costs), but that there were considerable deviations for the design and production phase (i.e. material investments in control panels and commissioning costs) if the cost was expressed per detector. Several reasons for these deviations were identified during discussions with the central project team. First, while the costs during the use phase can be expressed per detector, the relation between the number of control panels and the number of detectors is highly project-dependent and therefore it is unfeasible to estimate the initial costs solely based on the number of detectors. Therefore, the choice was made to express the cost per node (CPN, as in Figures 8.22 and 8.23) instead of per detector (CPD, as was initially chosen by the project team of Company γ), except for the revision cost (which only depends on the number of detectors). Second, the parameters that influence the commissioning costs were found to be underestimated by the experts. These parameters were adapted accordingly and the results already presented take this into account.

Value analysis In the value analysis for Case γ, the performance indicators marked in bold in Table 8.11 were subjected to a further investigation, documented in Section D.2 of Appendix D. The following conclusions were derived:

- The performance indicator '*effect on fire insurance tariffs*' was found to have a relatively small influence on the value of the FDS. The potential of combining an FDS and a fire insurance service was seen as limited, due to their limited mutual influence.
- The value component '*impact on fire safety risks*', which consists of the performance indicators '*effect on probability of (non-)fatal casualties in case of fire*' and '*effect on property damage impact of fire*', is key to the value of an FDS. However, deriving reliable estimates for these indicators is far from evident, as explained in Appendix D. Statistics were found that allow to get an impression of the order of magnitude of the impact of an FDS on the fire safety risks of a building, but they are certainly not representative, detailed and reliable enough to be able to estimate how much value could be added by adapting certain design parameters of the FDS. Therefore, the quantification of these indicators was not pursued any further.

8.3.5 Step 4: Improvement scenario analysis

Identification of improvement scenarios

The improvement scenarios for Case γ are presented in Table 8.13.

Analysis of improvement scenarios

The results of the quantitative analysis of the improvement scenarios of Table 8.13 are summarized in Table 8.14.

Some of these scenarios are discussed more in detail:

Table 8.13: Improvement scenarios to reduce cost for Case γ.

Parameter category	**Description of improvement scenario**
technical parameters	*C1*: increasing the technical lifetime of smoke detectors for revision from 5 years to 8 years *C2*: reducing the probability of failure per node from 0,3% to 0,1% by using higher quality components *C3*: renovating an outdated FDS gradually over a period of 5 years to smooth the capital requirements for the customer and to ensure continuity of operation. The control panels are replaced in the last year.
logistical parameters	*C4*: opportunistic maintenance: combining preventive and corrective maintenance tasks and revisions to reduce logistical costs.
activity parameters	*C5*: reducing the time for preventive maintenance with 30% through implementation of a more efficient work procedure. *C6*: using wireless smoke detectors instead of wired detectors *C7*: reducing the time for installing the cabling of one detector with 25% through the implementation of a more efficient work procedure or by outsourcing wiring activities to a specialized partner.

Scenario $C1$ is an example of how a significant improvement potential can arise because an input-based revenue mechanism lacks the ability to align the incentives of provider and customer for the minimization of energy and material resources to deliver a certain functionality. The currently applied revision period of five years is prescribed to building owners by fire insurance companies, but is in fact an outdated requirement. With current detector technology and the fact that the pollution of detectors in office buildings has diminished significantly since smoking bans were put in place around Europe, experts at Company γ indicated that the current revision period could easily be extented to at least eight years. Because the status of detectors is checked yearly, Company γ representatives indicated that their reliability would not be impacted. This simple adaptation would immediately reduce the in-service cost per detector with 12% to 22%. But because revision is currently paid 'per detector revised' (i.e. input-based), the provider is not keen on effectuating this optimization of the revision period, because this would reduce the income per contract. If a long term (e.g. 10 years) contract would be set up during which all life cycle support should be provided by Company γ and paid at a fixed annual rate, the right incentives would be in place to ensure that the FDS provider implements this improvement scenario.

The aim of analyzing improvement *scenario* $C3$ was to derive a cash flow model for the different renovation scenarios and to analyze their determining factors for Company γ. One scenario in particular will be discussed more in detail.

Table 8.14: The main results of the quantitative analysis of the improvement scenario examples of Table 8.8.

Parameter category	Description of improvement scenario
technical parameters	*C1*: For fifteen current customers of company C, the cost per detector was calculated if revision would be performed after eight instead of five years. This would result in an 'in-service' cost saving of between 12% and 22% per detector, depending on customer specific parameters (number of input/output modules, push buttons, etc). *C2*: If the failure probability per node would be reduced from 0,3% to 0,1%, the 'in service' cost per node would be on average 12% lower. *C3*: A detailed analysis of two different renovation scenarios was performed. In scenario 1, the number of detectors in the renovated system would remain the same, while in scenario 2 the number of detectors would be increased with 5 to 10%. All costs and investment requirements for the customer of these two scenarios were calculated over the 15 year contract period (cfr. infra).
logistical parameters	*C4*: : Opportunistic maintenance could lead to an 'in service' cost saving per node of 2,8%.
activity parameters	*C5*: A 30% reduction of the time for preventive maintenance would result on average in a 5,5% reduction of the 'in service' cost per node. *C6*: The maximum 'budget' per detector was determined, based on the wiring cost per detector. This budget should compensate for higher component prices and battery replacements. However, before this option is pursued, the impact on the reliability of the FDS should be assessed in detail [53]. *C7*: A 25% reduction of the cabling time per detector would result in a 7% 'initial' cost saving per node.

The starting point of this analysis is a customer that has an outdated FDS that should be replaced within the next five years. Company γ representatives indicated that this scenario represents a significant share of their installed base. In the traditional way of working, these customers would be offered a complete renovation in year 1 (installation, material investments, commissioning), sold input-based, and separately a life cycle support (maintenance, revision, battery replacements) contract. The disadvantages of this model are that the size of the investment would trigger customers into requesting proposals from more competitors, which in its turn would give rise to increased price based competition. On the other hand, the fact that the service contract is offered separately would imply that customers who procure a renovation of their FDS from Company γ might still decide to involve other competitors (e.g. building maintenance companies) for this (typically more profitable) part. Therefore, the following scenario was developed:

- Company γ and the customer enter a contractual agreement whereby over a period of fifteen years, the renovation and maintenance of the FDS is ensured according to applicable standards and requirements, at a fixed annual rate per detector.
- Distributed evenly over the first five years, Company γ replaces all detectors D and adds in total an extra 5-10% of detectors $D*$ to ensure that the building measures up to all applicable fire safety standards. During the first four years, the old control panels would still be in use. The technical feasibility of this aspect was ascertainted. These costs are all included in the fixed annual rate.
- In the fifth year, additionally, all control panels are replaced, together with the last 20% of detectors D and the last portion of the extra detectors D*.
- Over the total period of fifteen years, all life cycle services are performed (revision, preventive and corrective maintenance, battery replacements) on the complete installation.

The cash flow model of this scenario is represented in Figure 8.27. As can be seen from this figure, there is a significant uncertainty in all cash flows that can be attributed to the uncertainties in the input parameters. The most important input parameter uncertainties that determine the total NPV calculated by aggregating all cash flows of Figure 8.27 are the time for preventive maintenance per node, the material cost into control panels and the reliability of detectors. These parameters are the key determinants of the profitability of this renovation service for Company γ.

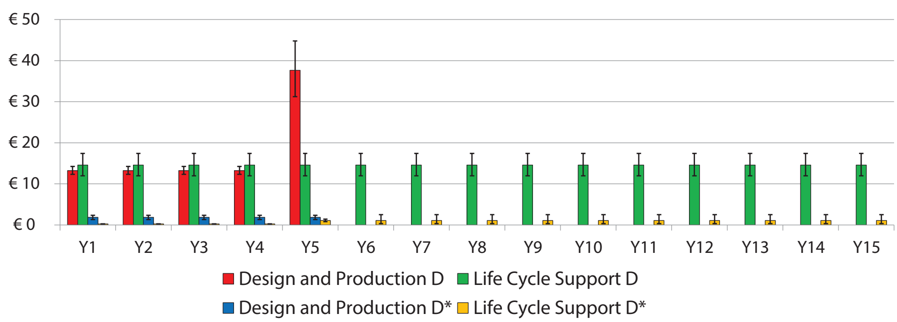

Figure 8.27: Cash flow model of all costs related to the gradual renovation scenario (cfr. improvement scenario $C3$ in Table 8.13). The error bars indicate the 10^{th} and 90^{th} percentile, the colored bars the average cost per detector.

Conclusions for Case γ

In Table 8.15, the improvement scenarios are linked to PSS options $PSS_{\gamma 1}$ to $PSS_{\gamma 5}$ (cfr. Figure 6.3 and Table 6.3).

Table 8.15: Matrix linking the improvement scenarios $C1$ to $C7$ of Table 8.13 with the five PSS options for Company γ.

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
$PSS_{\gamma 1}$	X	X		X	X	X	X
$PSS_{\gamma 2}$	X	X		X	X		
$PSS_{\gamma 3}$	X	X	X	X	X	X	X
$PSS_{\gamma 4}$	X	X		X	X		
$PSS_{\gamma 5}$	X	X		X	X	X	X

The following are the conclusions for Case γ:

- Most of the improvement scenarios are related to a reduction of the 'in service' cost and can be tapped in each of the five PSS options considered. The combination of scenarios $C1$, $C2$, $C4$ and $C5$ can lead to a significant reduction of the in-service cost per node, i.e. with more than 37% (if the savings due to $C1$ are estimated at 17%).

- If PSS options are considered whereby the initial investment is included (i.e. $PSS_{\gamma 1}$, $PSS_{\gamma 3}$ or $PSS_{\gamma 5}$), it is especially important to reduce the costs of wiring. As indicated in Section 8.3.4, wiring costs are responsible for a large share of the variability of the initial investment in an FDS. This variability can be reduced either by finding technical or operational solutions to reduce the wiring cost per node (e.g. better training or implementation of wireless detectors) or by outsourcing wiring activities to a specialized partner for a fixed rate per node or per detector. Besides optimization possibilities in the wiring costs, the advantages of these three PSS options are related to the lowered investment barriers for customers and therefore the potential to increase the customer base (i.e. Mechanism 4 of Section 3.5). However, because in these PSSes the investments are borne by Company γ, they were considered to be more risky. In case of non-payment, Company γ cannot recuperate most of the value of the FDS.

- Members of the central project team pointed out that the main business potential of option $PSS_{\gamma 3}$ is to be found in its ability to 'change the competitive environment' (i.e. Mechanism 3 of Section 3.5). In case a customer would renovate the FDS in one year only, more companies would be sollicited for a proposal and the focus of the customer would be on the initial investment costs. In case the renovation is spread out over a period of several years, the number of competitors and the customer's focus on price can be kept lower. Therefore, again in this case study, as in Case β, we are confronted with an essential mechanism besides cost reduction or value improvement; again a mechanism for which a reliable ex ante quantification is deemed unfeasible (i.e. a reliable estimate of how many customers could be convinced due to the changes in the competitive environment). However, the usefulness of the proposed methodology was attested by the company representatives, who stated that for the preparatory analysis of $PSS_{\gamma 3}$ it is essential to gain insight in the total cost per node of the renovation scenarios considered in C3 and in the key determinants of its profitability.

Generic conclusions

The following *generic conclusions* can be derived from application of the methodology of Chapter 7 for Case γ:

- This case illustrates how the cost improvement potential of a PSS can be analyzed, focusing on the production and use phase of a highly customized system that consists of many different types of components and that is subject to standards and requirements from different actors. Due to the significant uncertainties in the inputs, specifically in customer specific, technical and activity parameters, a stochastic approach to quantify cost was found to be indispensible. However, due to the many possible combinations of components, it was necessary to delimit the scope of the analysis and to consider specific ranges of parameters (such as the area per sirene, push button, etc.) to derive useful conclusions.

- When a PSS is analyzed for a complex system that consists of a combination of different components, it is crucial to choose an appropriate cost object. The sensitivity analysis presented in Figure 8.23 was perceived as much more informative if performed per node than if performed per detector, because otherwise the uncertainties regarding the customer specific parameters would dominate the variation of the output. Moreover, this case illustrates how an appropriate pricing unit can be chosen by analyzing the variability of the distributions of the cost per unit (i.e. per node, detector or m^2 in this particular case). Initially, Company γ representatives stated that a price for offering $PSS_{\gamma 1}$ could be set per detector, but as indicated by Table 8.12, this would increase the risk of a non-profitable contract, and therefore a PSS with a price per node was preferred.

- This case illustrates that a reliable quantification of the main value aspects of an investment is not always possible (e.g. impact of fire), due to the abscence of reliable data on which estimates could be based.

- Even in cases where the essential mechanism that determines the business potential of a PSS is not cost reduction, the proposed methodology can be applied to gain insight in the cost structure of a PSS that targets the expansion of the customer base or changes in the competitive environment.

- For Company γ representatives, the main outcome of this study was the identification of the key determinants of the cost per node and per detector of an FDS, whereby specifically the importance of the costs for cabling and of the duration of preventive maintenance per detector was perceived as insightful. At the outset of this study, the company representatives only indicated that many different parameters influence the LCC of an FDS, but they could not name which particular parameters are dominant. Furthermore, the detailed analysis of the improvement scenarios (specifically $C1$ and $C3$) was deemed insightful.

8.4 Case δ: Diamond polishing systems

This section covers a case study about an investment good that is not yet fully developed (an automatic diamond polishing system) in a specific context, the diamond gemstone industry. In Section 8.4.1, we will present some background; first on diamonds and the diamond gemstone industry and then on the system that is the focus of our study. Subsequently, in Sections 8.4.2 to 8.4.5, the four steps of the methodology are discussed.

8.4.1 Background: diamond gemstones and grain independent polishing

Diamond gemstones are not consumed for their intrinsic utility but for the impression they make on others [182]. Therefore, they have a negligible *value in use* but a significant *exchange value*. The exchange value of a diamond depends on a complex interaction of different parameters, known in the industry as the '*four C's*': *color* (as a general rule a white diamond is more valuable than a diamond that is more yellow), *clarity* (which depends on the number of material defects, evaluated according to a clarity grading scale), *cut* (which reflects the symmetry, proportions and polish of a diamond) and *carat* (the stone's weight expressed in carats, i.e. units of 200 mg). The pricing of diamonds demonstrates anomalies, such as price premiums of 25% that customers are willing to pay for a 0,50 ct diamond over a 0,49 ct diamond [182].

The value chain of the diamond gemstone industry is highly fragmented. Between the exploration of diamond ore and the retail sales to the final consumer, a diamond travels along the '*diamond pipeline*', that spans activities that are dispersed both geographically and organizationally. From 'mine to finger', a diamond typically changes hand between a dozen stakeholders and covers a distance of several 10.000 kilometers. For several centuries, the city of Antwerp has played a dominant role in this global network. At present it is still the global trading capital. It is stated that more than 80% of the world's rough diamonds and more than 50% of the polished diamonds are traded in one of its diamond exchanges [165]. From the Middle Ages until the early 1980s, Antwerp was the global center of diamond cutting and polishing, but over the last decades this position was lost to polishing centers in Asia, due to the availability there of low cost labor. At present, cutting and polishing in Antwerp is restricted to high

For confidentiality reasons, most of the numerical values presented in this section are expressed relatively or, if monetary values are provided, they were multiplied with an unspecified scale factor.

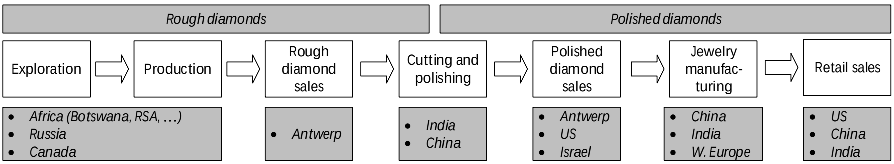

Figure 8.28: The 'diamond pipeline', with an indication of the most likely geographical location of each stage (based on information in [165]).

value added diamonds [218]. In Figure 8.28, the diamond pipeline is represented, whereby for each step its most likely geographic location is indicated (based on the analysis of Prinsloo et al. [165]).

The 'cutting and polishing' stage, which is the focus of this case study, consists of the steps represented in Figure 6.2. These steps can be characterized as follows[19]:

- In the *planning* step, the rough diamond is analyzed by using a scanner to map the external geometry and internal defects and 'impurities' in the rough material. Subsequently, a decision is made about the type of gemstones that will be produced from the rough material. The main goal of this step is the maximization of the commercial value of the stones. Specialized software is available for this optimization.
- In the *sawing* step, the rough diamond is sawn into several pieces. Mostly, laser technology is applied.
- In the *bruting* step, the rough stone is ground into a circular outline. As a result, the '*girdle*' is shaped and thus the top and bottom of the stone are determined. A *round brilliant cut* diamond (currently the most popular diamond shape [71, 226]) is characterized by a round girdle.
- In the *polishing* step, all surfaces of the diamond are polished by using a cast iron disk (the *scaife*) that is charged with diamond powder [181]. Thus, all facets of the diamond (57 for a round brilliant cut) are finished.
- In the *final grading* step, the cut quality of the finished stone is analyzed.
- Optionally, the diamond can be sent to a gemological laboratory (e.g. HRD Antwerp, GIA) for *certification*. There, the diamond's authenticity is confirmed and its essential characteristics (i.e. the four C's) are described.
- In between these steps, that are often not performed at the same location, a *transport* step might be included. A few specialized companies offer a customized transport service that includes freight insurance.

[19]This overview was mainly obtained by interviewing representatives of Company δ and of diamond processing companies.

Now we will take a closer look at the polishing step. The traditional polishing process of a diamond requires that the appropriate polishing direction (‘*grain*’) is identified by a skilled craftsman, because the removal rate depends significantly on the polishing direction due to the diamond’s crystalline structure [245]. This factor makes diamond polishing quite labor intensive and requires highly skilled polishers. *Grain Independent Polishing (GIP)* is a technological innovation, developed by Company δ, that allows to polish diamonds independent of the grain structure, in a cold process. Therefore, with GIP the polishing process can be completely automated.

There are different possibilities for the valorization of GIP: the core technology can be licensed or implemented in a manual installation or it can be embedded in a fully automatic polishing system, brought to the market as an investment good. But, as we have seen in Chapter 6 (cfr. Figure 6.3), several PSS options are possible as well, whereby the automatic diamond polishing system is not sold as a product but rather commercialized as a ‘diamond polishing service’, charging customers for delivered functionality, i.e. ‘*per finished carat*’. As can be seen in Figure 6.3, this polishing service can be embedded in a wider ‘diamond processing service’, whereby other process steps between rough and polished diamond are included as well (e.g. planning, sawing, bruting).

A particular advantage of a PSS model for this specific case is that it allows to keep more control over the technology, while if GIP is commercialized as an investment good to customers in India and China, it is expected by Company δ representatives and industry experts that it is only a matter of time before intellectual property rights (IPR) are infringed. It is widely acknowledged that IPR infringement is not uncommon in these countries [246].

Although the core technological innovation of GIP has been accomplished, the research project is still ongoing to develop a completely automated solution. Therefore, there are still many uncertainties about the technical parameters of the GIP process. The presented case study allows to direct the attention of Company δ’s R&D team towards the technical parameters that have the highest impact on the value of this technology.

Moreover, one specific goal should be kept in mind: Company δ representatives stressed the importance of employing the GIP technology to strengthen the Belgian diamond gemstone industry in particular in comparison to Asian diamond cutting and polishing centers. Therefore, a specific focus on diamond segments for which the cutting and polishing has shifted to Asia over the last decades has been suggested. As we will see, this specific focus allows to perform value quantifications in relation to a competing offering, according to Strategy 4 of Section 7.3.1.

8.4.2 Step 1: Goal and scope definition

Customer segments

The customer segmentation basis chosen is *the weight category of the stone after polishing*, expressed in carats, according to which the following segments were identified:

- Segment A (0,25 – 0,39 ct)
- Segment B (0,40 – 0,49 ct)
- Segment C (0,50 – 0,69 ct)
- Segment D (0,70 – 0,99 ct)

These segments do not represent the complete market for diamond gemstones but rather the 'middle bracket'. Many high value diamonds ($> 1ct$) are still being polished manually by specialized workers in Antwerp and are therefore not within the scope of this case study. Smaller diamonds ($< 0,25ct$) were seen as more challenging to be processed with the new technology. The aforementioned segments are delineated based on industry standards (e.g. the same categories are used in commercially available price lists, such as RAPAPORT). Typically, moving to a higher segment is associated with a significant price hike.

Basis of evaluation

In Table 8.16, the functional results of an automatic diamond polishing system (DPS) are expressed on different levels of abstraction, according to the guidelines presented in Chapter 4.

Table 8.16: Functional results of an automatic DPS on different levels of abstraction.

Abstraction level	Functional result
Demand-fulfillment result	Transform a rough diamond into a finished gemstone with maximum value.
Environment-centric functional result	Polish one diamond according to predefined specifications set to the stone (symmetry, proportions and polish quality).
Solution-centric functional result	Operate a DPS according to solution-centric specifications (e.g. positioning accuracies with regards to angles and depth).
Structural elements	Diamond polishing system (DPS), including two identical modules for roughing, one module for finishing, a positioning system, a cleaning system and a measurement system.

For our analysis, functional results on two levels of abstraction are relevant:

- The *demand-fulfillment result* is the necessary perspective to investigate PSS options whereby, besides polishing, other process steps are included in Company δ's offering.
- The *environment-centric result* allows to focus on the polishing step in particular, and allows to analyse the additional value of GIP in relation to polishing in China and India.

System boundaries

The system boundaries are presented in Table E.1 of Appendix E.

Cost components

The cost components are related to the new process, i.e. to a DPS wherein the GIP technology is applied in an automated set-up. Since two possible functional results were identified as evaluation basis, two Cost Breakdown Structures are determined (cfr. Figure 8.29):

- For the environment-centric functional result, only the costs of bruting and polishing with the automatic DPS are taken into account. These are the grey boxes of Figure 8.29. This corresponds to a diamond polishing service whereby customers deliver stones that are already planned and sawn, and pick them up after they are polished according to a customer defined planning.
- For the demand fulfillment result, all costs of the process steps in the cutting and polishing stage of the diamond pipeline are included. These are the white and the grey boxes of Figure 8.29. This corresponds to a diamond processing service whereby customers deliver rough stones and pick up finished stones with maximized value.

Value components

The value components and corresponding performance indicators identified for Case δ are presented in Table 8.17.

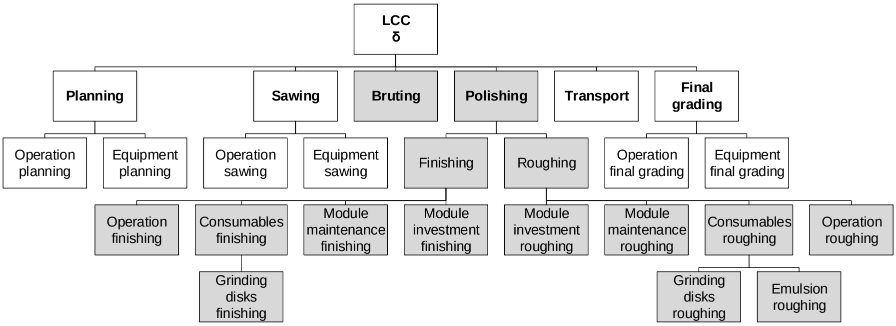

Figure 8.29: Cost Breakdown Structure for Case δ.

Table 8.17: Value components and corresponding performance indicators for a diamond polishing system (Case δ). The indicators displayed in bold were chosen for further analysis.

Value aspects	Value components	Performance indicators
Assurance	Conformity to norms and standards	• Conformity to diamond grading regulations [binary] • Conformity to international labor regulations [binary] • Conformity to Kimberley Process Certification scheme [binary]
Convenience	Ease of coordination	• Time to coordinate one batch of diamonds [hours]
Responsiveness	Responsiveness to orders	• **Total leadtime of one batch of diamonds [days]**
Safety	Impact on risk of damaging stones	• **Probability of damage** [%]
Flexibility	Ability to facilitate external cost savings or revenue increase	• **Effect on transport costs** [€]
Productivity	Accuracy	• Ability to follow planning, expressed as the ratio of forecasted and realized value [%] • Cut quality, expressed as symmetry, proportions and polish quality [various]

8.4.3 Step 2: Model development

The model to quantify the cost and value per functional result of a DPS was constructed according to the following logic:

- The *cost per functional result* represents the cost in US$ per carat[20] of either the bruting and polishing steps with the DPS (if the environment-centric functional result is the evaluation basis) or of all process steps discussed in Section 8.4.1, if the demand-fulfillment result is the evaluation basis.
- The *value per functional result* was quantified according to Strategy 4 of Section 7.3.1, i.e. by determining the price of competing offerings (the cost of polishing and bruting in China or India) and by determining the monetary additional value of the DPS over these outsourcing scenarios through an estimation of the maximum WTP for selected performance indicators of Table 8.17.

The structure of the simulation model with input parameters in different categories is depicted in Figure 8.30.

For quantifying the value of a DPS, the following equation was applied:

$$V_M = P_{CO} + \Delta V_M = P_{CO}^{CN/IN} + WTP_{LT}^{max} + WTP_{TC}^{max} + WTP_{PD}^{max} \quad (8.2)$$

In Equation 8.2, V_M is the monetary value of the DPS, ΔV_M is the monetary additional value versus the competing offering, $P_{CO}^{CN/IN}$ is the price of the competing offering, which is in this case the cost for polishing in China (CN) or in India (IN), WTP_{LT}^{max} is the maximum WTP for the gain in leadtime versus the competing offering, WTP_{TC}^{max} is the maximum WTP for the reduction of transport costs vs. the competing offering and WTP_{PD}^{max} is the maximum WTP for the reduction of the probability of damage vs. the competing offering. All terms are expressed in US$ per carat. The other performance indicators of Table 8.17 were considered to have a minor impact on the total additional value, except for the performance indicators related to the accuracy of the DPS. These last indicators can be important for certain stones (e.g. with strict requirements on symmetry), but in coordination with Company δ representatives, the decision was made not to consider them in the value analysis.

[20]When 'cost per carat' is mentioned, it will be assumed that the cost is expressed per carat of the final weight, not per carat of the initial weight of the diamond, unless explicitly specified.

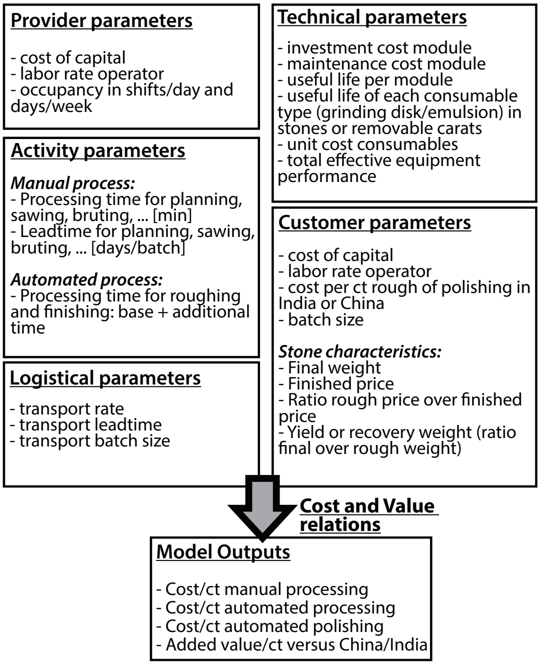

Figure 8.30: Model structure for Case δ.

According to the chosen value quantification strategy, a PSS model can only have a business potential if $V_M > C_{DPS}$, with C_{DPS} the cost per carat of the automatic diamond polishing system. The difference $V_M - C_{DPS}$ is the sum of provider and customer surplus and is the additional value that can be realized by the DPS over its cost. In order to have a sustainable business situation, both surpluses should be positive. The profitability of an automatic DPS is secured if the total margin $V_M - C_{DPS}$ is maximal.

For estimating the terms of Equation 8.2, the following assumptions were made:

- WTP_{LT}^{max}: The maximum WTP for a gain in leadtime equals the capital cost the diamond processing company can gain due to the time advantage in days. It is calculated as follows:

$$WTP_{LT}^{max} = WACC \cdot \frac{\Delta d}{365} \cdot RP \tag{8.3}$$

  with $WACC$ the yearly weighted average cost of capital of the diamond processing company, Δd the time advantage in days and RP the price of the rough material per carat final weight.

- WTP_{TC}^{max} is equal to the transport cost for outsourcing to China/India.
- WTP_{PD}^{max} represents the potential loss of value due to extra risks of outsourcing to China/India versus polishing with the DPS. If a stone is damaged during polishing, a certain percentage of the value of the rough material is lost (e.g. 50%).

8.4.4 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table E.2 of Appendix E, the main information sources of Case δ are listed. As can be seen from this table, the most important information sources are (potential) customers for Company δ, i.e. diamond processing companies.

Uncertainties and risks

For Case δ, scenarios were defined according to the following parameters:

- the *customer segment* or weight category of the finished stone (A, B, C or D)
- the *occupancy level of the DPS*, which determines the number of available machine hours, taking into account a total effective equipment performance [131] ratio of 0,75 to 0,85. Each occupancy scenario is determined by S, the number of shifts per working day (1, 2 or 3), and D, the number of working days per week (5 or 7). The following scenarios were taken into account: *5D1S*, *5D2S*, *7D2S* and *5D3S*.
- the *combination of technical and activity parameters of the DPS*. Four scenarios were considered:
    - In the 'variable' scenario, the technical and activity parameters related to the DPS (e.g. tool life of the polishing disk, processing time) are modeled as either a PERT or Uniform distribution.
    - In the 'optimistic', 'most likely' and 'pessimistic' scenario, all technical and activity parameters related to the DPS are modeled as a single number, namely the optimistic, most likely and pessimistic estimate respectively.

- the *geographical location of the competing offering*. Scenarios '*vs. China*' and '*vs. India*' determine the additional value versus manual polishing in China or India.
- the *inclusion of 'tension stones'*. Tension stones are stones where due to internal material strains, damage can occur during the cutting, bruting or polishing steps. Additional processing times in these steps might be applicable, depending on how large the internal tension is. Industry experts tend to discern tension stones into different categories (cfr. Table E.3). One scenario was added where tension stones were taken into account, to have a clear view on how the additional value and cost of polishing tension stones differs from the current situation. The number of tension stones in a batch of rough material is highly variable. One diamond processing company representative estimated that the number of tension stones in a batch can be anywhere between 10–80%.

The choice of the most important statistical distributions that represent the uncertainties in the input parameters is clarified in Table E.3 of Appendix E.

Output analysis and validation

In this section, some results of the output analysis for Case δ are presented, first of the analysis of the current way of working (manual processing), then of the cost analysis of automatic polishing and finally of the value analysis of automatic polishing.

Analysis of manual processing From information provided by three representatives of diamond processing companies, the impact of each step of the cutting and polishing stage of the diamond pipeline (cfr. Section 8.4.1 and Figure 6.2) on cost and on the main value aspects of Table 8.17 was analyzed. Three point estimates were provided for all input parameters related to the current, manual way of working (e.g. times for polishing, planning, etc). These estimates were used as inputs of a Monte Carlo simulation model (5000 simulation runs) and the distributions of the cost per carat for the different steps in different locations were determined, cfr. Figure 8.31. As can be seen from this figure, the polishing step is dominant from a perspective of both cost and of leadtime. Six different scenarios were identified related to the geographical location of the different steps (e.g. planning and sawing in Belgium, bruting and polishing in India). For each scenario, the total cost was determined.

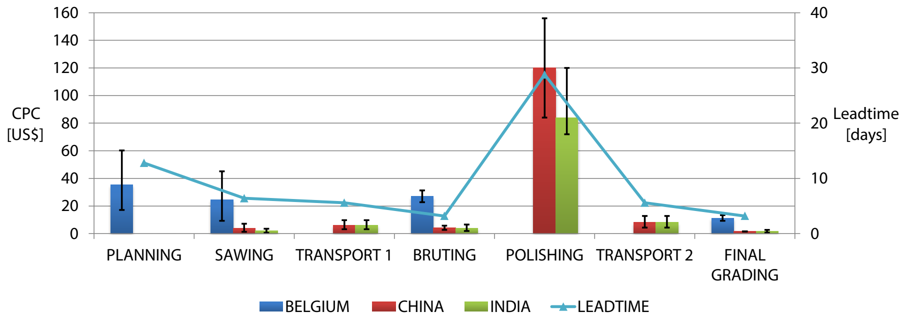

Figure 8.31: Impact of all main steps in the cutting and polishing stage on the cost per carat (CPC) of final weight, in US$ (the colored bars represent the averages for different geographical locations and the error bars indicate the range from 10^{th} to 90^{th} percentile) and on the leadtime in days per batch of diamond that is processed.

Besides the criteria cost and leadtime, others were analyzed as well, i.e. the impact on the risk of damaging the stone in the different steps and the impact on the accuracy. It was determined that the sawing step has the highest impact on the risk of damaging the stone, followed by the polishing step. Overall, the cost of 'accidents' (i.e. instances whereby a tension stone is damaged during processing, resulting in a percentage of value lost) is, for what was considered to be the most common geographical scenario[21], responsible for on average 16,6% of the cost per carat (10,2% for sawing accidents and 6,4% for polishing accidents), calculated over all stones. This cost of damage is highly variable and mainly depends on the number of tension stones in a batch.

With regards to accuracy, the critical step in the process is the planning step. Decisions made in the planning step are crucial for the value that can be extracted from a rough stone and require a great deal of skill and experience. One informant stated that a wrong decision at this stage will overshadow all possible gains made in later steps (including those related to the polishing cost). Apparently, many diamond processing companies consider the planning step to be part of their core competences and would not easily outsource this responsibility to other actors.

Cost analysis of polishing with an automatic DPS For different scenarios related to the weight category (A, B, C or D) and the occupancy of the modules ($5D1S$, $5D2S$,$7D2S$ or $5D3S$), the cost per carat final weight of the automatic

[21]With planning and sawing performed in Belgium and polishing outsourced to India.

DPS was determined. The cost components included are the grey boxes of Figure 8.29. The main input parameters of the Monte Carlo simulation model (5000 iterations) that determine this cost were provided by Company δ specialists. The results of the analysis are presented in Figure 8.32.

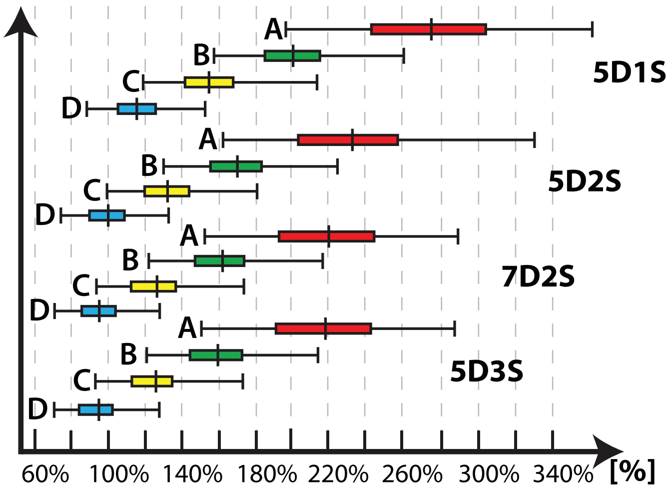

Figure 8.32: Boxplots of the cost per carat final weight, for different scenarios for polishing with an automated DPS. The average cost of scenario $5D2S$ for sergment D is chosen as reference (i.e. 100%).

From Figure 8.32 we conclude that there is a significant difference between the costs per carat for the different weight categories. There is some variation in the cost *per stone* of polishing with the DPS that depends on the size of the stone (and the number of carats that is removed), but this difference is relatively limited. Therefore, smaller stones (i.e. categories A and B) have a significantly larger cost per carat final weight than larger stones.

Due to the fact that the maintenance costs and the amortization of the investment price depend on the occupancy scenario, a lower occupancy (i.e. $5D1S$) results in a significantly higher cost per carat. The differences between the three other occupancy scenarios are less pronounced.

In Figure 8.33 the decomposition of the average cost *per stone* of polishing with an automatic DPS is presented. Half of the costs are related to the specialized grinding disks of the finishing process. For occupancy scenario $5D1S$ (not shown in Figure 8.33) the maintenance and investment cost still accounts for 29% of the average cost, while for scenario $5D2S$ this share is reduced to 17%. For higher occupancy scenarios, the dominant contribution of the polishing disks is even increased.

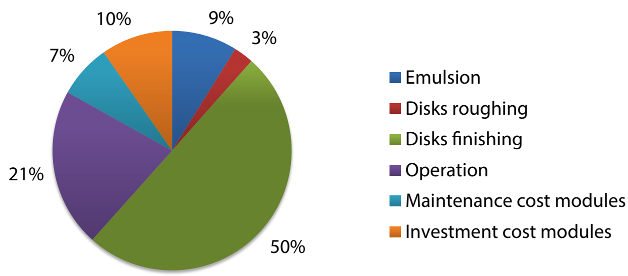

Figure 8.33: Pie chart of the average cost *per stone* for polishing with an automatic DPS, for occupancy scenario $5D2S$ and weight category D, discerned into the main cost categories.

The variability of each boxplot of Figure 8.32 can be analyzed separately through a sensitivity analysis, to identify the key factors that determine whether the cost per carat is at the lower or higher limit of the range for a specific scenario. For example, for occupancy scenario $5D2S$ and weight category D, in Figure 8.34 a tornado chart is presented that depicts the evolution of the average cost per carat final weight.

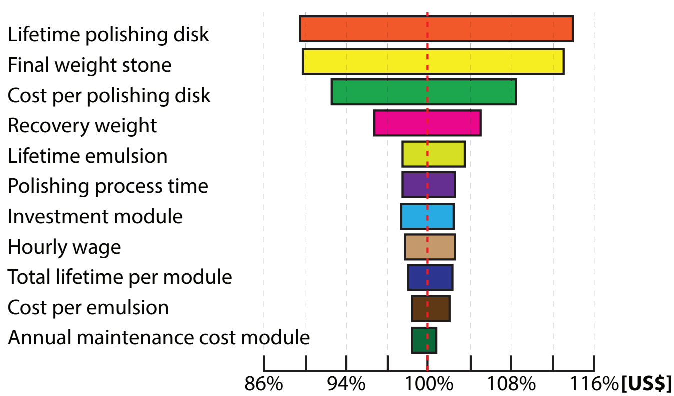

Figure 8.34: Tornado chart depicting the evolution of the average cost per carat final weight for polishing with an automated DPS, for occupancy scenario $5D2S$ and weight category D, as a function of selected input parameter variations.

Figure 8.34 demonstrates that the polishing disks are the main driver of the variation of the polishing cost, both with regards to their lifetime, expressed as a number of stones that can be processed and to their cost per disk. The maintenance and investment costs of the modules are less important for the variability of the output distribution. It should be mentioned that the development project of the automatic DPS is still ungoing, and the main technological uncertainties are related to the finishing stage of GIP, while the roughing stage has already been optimized. Figure 8.34 ranks the input parameters according to the highest relative contribution on the cost per carat. Thus, the attention of the research team of Company δ can be focused on the optimization of these critical design parameters.

Value analysis of polishing with an automatic DPS For the value analysis, one specific occupancy scenario ($5D2S$) was chosen, since Company δ representatives indicated that in the medium term this is the most realistic option. The main output is the additional value of a DPS over its cost, which can be calculated, as elucidated in Section 8.4.3, as $V_M - C_{DPS}$. The different terms in Equation 8.2 were taken into account as follows:

- P_{CO} is the price that diamond processing companies pay for outsourcing a batch of diamonds to China/India for polishing. Three point estimates were derived from four diamond processing companies of the market prices they pay to their Asian subcontractors. These prices are always expressed per carat rough material and, remarkably, the difference in cost per carat over the weight categories is relatively limited.

- WTP_{LT}^{max} (the DPS's effect on leadtime) was determined according to Equation 8.3, whereby the time advantage in days of polishing with a DPS in Belgium assumes that from the sum of the leadtimes of the steps bruting, polishing, transport 1 and transport 2 of manual processing (cfr. Figure 8.31) the estimated leadtime of processing the same batch with the DPS in Belgium was subtracted. The WACC of a diamond processing company was estimated to be between 8 and 12%.

- WTP_{TC}^{max} (the DPS's effect on transport cost) was determined by quantifying the transport cost. The largest share of the transport cost is related to insurance fees, and therefore the cost for transporting diamonds is expressed in a fee per 1000 US$ of transported goods. Both in the leadtime and transport cost estimation, we assume that there are two transports necessary (i.e. from Belgium to China/India and the return connection).

- For WTP_{PD}^{max} (the DPS's effect on the probability of damaging a stone), a separate analysis was performed. The main difficulty of quantifying this term lies in the fact that, although there is an indication that the new automatic polishing technique reduces the probability of damage, there are only very limited data available to quantify this effect. Therefore, unless explicitly mentioned, this influence is not taken into account in the following analyses.

For the four different scenarios related to the combination of technical and activity parameters of the DPS (variable, optimistic, pessimistic and most likely scenario), the additional value per carat $V_M - C_{DPS}$ was determined. For three scenarios, variable, optimistic and pessimistic, the results are presented per weight category and per reference scenario (versus China or versus India) as boxplots, in Figures 8.37, 8.35 and 8.36. 5000 simulation runs were performed for each scenario. The following conclusions were derived:

- The additional value versus China is significantly larger for all possible scenarios than that versus India, due to the difference in outsourcing costs.
- If the additional value in the optimistic and the pessimistic scenario are compared, one can conclude that the optimization of the technical and activity parameters related to a DPS will certainly have a profound impact on the profitability of this new technology.
- For segment A, the additional value is always negative, even in the most optimistic scenario, due to the relatively large cost per carat of polishing with the automatic DPS and limited savings in capital and transport costs. Therefore, in any possible scenario segment A is not a profitable segment for polishing with an automatic DPS.
- In most of the scenarios, the additional value for segment D is positive, both versus China and India, except for the pessimistic scenario, where the probability that it is negative is 98% versus India and 72% versus China. In the variable scenario, the additional value for segment D versus India is positive in 85% of the cases.
- For segment B, the additional value is only positive for optimistic process parameters versus China (in 83% of the cases).
- For segment C, the additional value is positive versus China in the variable scenario in 70% of the cases and versus India in 15% of the cases. In the optimistic scenario, the additional value is always positive and in the pessimistic scenario it is always negative.

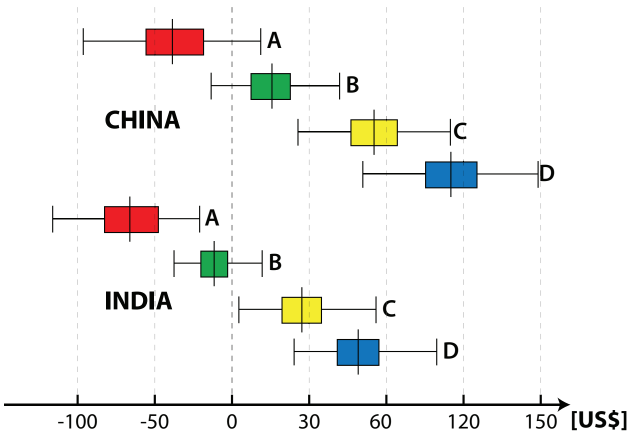

Figure 8.35: Boxplots of the additional value per carat of an automatic DPS versus polishing in China/India, for the *optimistic scenario*, for occupancy scenario $5D2S$ and for weight categories A, B, C and D. A scale factor is applied for confidentiality reasons.

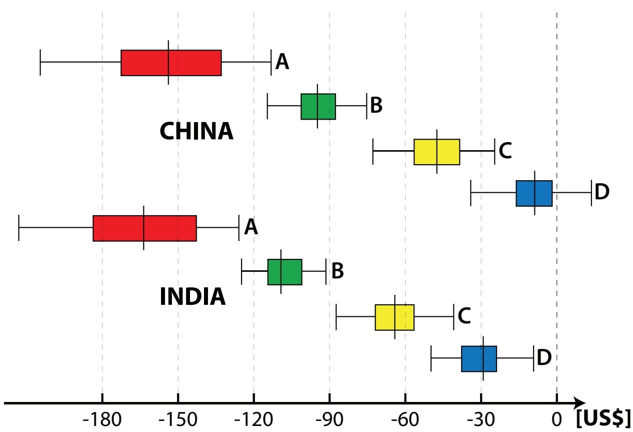

Figure 8.36: Boxplots of the additional value per carat of an automatic DPS versus polishing in China/India, for the *pessimistic scenario*, for occupancy scenario $5D2S$ and for weight categories A, B, C and D. A scale factor is applied for confidentiality reasons.

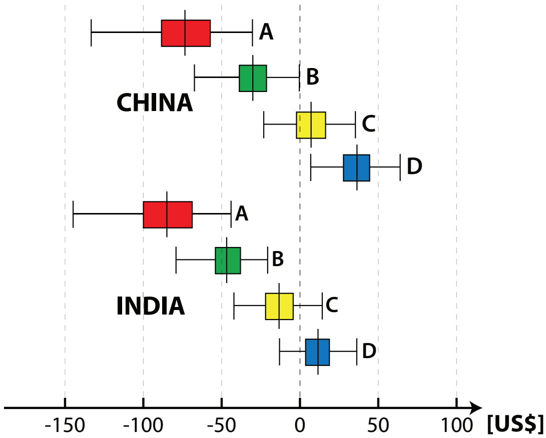

Figure 8.37: Boxplots of the additional value per carat of an automatic DPS versus polishing in China/India, for the *variable scenario*, occupancy scenario $5D2S$ and for weight categories A, B, C and D. A scale factor is applied for confidentiality reasons.

Subsequently, the variability of the additional value was analyzed. As can be seen in the boxplots of Figures 8.37, 8.35 and 8.36, as a general observation the variability of the additional value is reduced for highter weight categories. This can be explained by the fact that the cost for polishing with an automatic DPS is similar for different stone sizes, and because the additional value is calculated per carat, for smaller stones it is dominated by the variability of C_{DPS}[22].

In Figure 8.38 the result of a sensitivity analysis is presented: a tornado chart of the additional value *per stone*, with a ranking of the main input parameters by their relative contribution to the additional value per stone, for segment D, versus China and occupancy scenario $5D2S$. Besides the activity and technical parameters related to the DPS (cfr. Figure 8.34), the following parameters are dominant:

- The *final weight of the stone*: for larger stones, the polishing cost with a DPS per carat is cheaper (cfr. Figure 8.32) while within one segment the outsourcing costs are charged per carat rough material. Additionally, the final value of the stone is in general larger for heavier stones (and thus the additional value due to transport and capital savings is more prominent).

[22] This effect is largely compensated for segment C, for which the additional value is slightly more variable than that of the additional value for segment B because the final value per carat spans a larger range, cfr. Figure E.2 in Appendix E.

- The *final value per carat*: this parameter determines the transport and capital savings, because both are driven by the value of the shipment. A detailed sensitivity analysis of the additional value as a function of this parameter was performed, the results of which are presented in Section E.2 of Appendix E.
- The *recovery weight*: remarkably, if a stone with a particular final weight corresponds to a rough stone with a low recovery weight (i.e. more carats that are polished off the stone), the additional value is higher than if it had a high recovery weight. The main reason should be found in the way outsourcing prices are determined: a price per carat rough is charged for polishing in China/India, while for polishing with an automatic DPS, the price per stone is only slightly higher if more of the stone should be polished away. This limited dependency can be explained by the fact that the cost of the finishing operation is dominant and independent of the recovery weight. Thus, the additional value is higher for lower recovery weights.

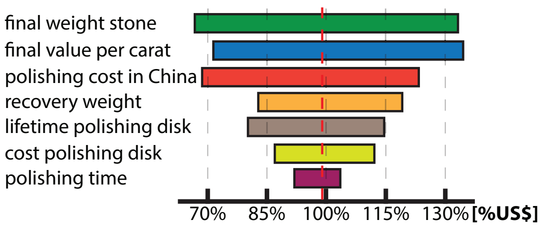

Figure 8.38: Tornado chart depicting the evolution of the average additional value of a DPS *per stone*, for occupancy scenario $5D2S$, weight category D and the variable scenario, versus China, as a function of selected input parameter variations.

To assess the potential profitability of operating an automated DPS facility, the additional value can be expressed relatively to the average polishing cost, cfr. Figure 8.39. The 10^{th}, 50^{th} and 90^{th} percentile of the additional value are presented for four scenarios a combination of segment C or D and in comparison to China or India. These values are the maximum profit margin (provider surplus) that can be charged on top of the polishing cost. For each scenario, the profitable market share is given as well, i.e. the probability that a stone for that particular scenario will have a positive additional value. The first scenario, *D China*, could be catered with comfortabe profit margins, as in 90% of the cases the additional value is higher than 35% of the cost. The margins for *D India* are considerably lower but still feasible. Thus, the observation that

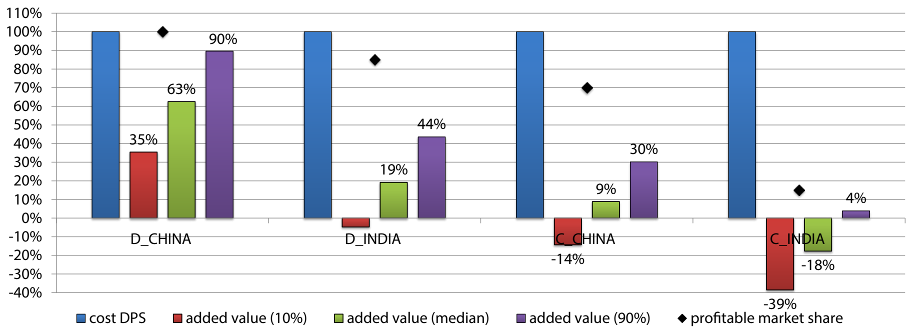

Figure 8.39: Profitable market share and 'variable' additional value (10^{th}, 50^{th} and 90^{th} percentile) per carat of polishing with an automatic DPS versus polishing in China/India, expressed relatively to the cost of polishing with an automatic DPS according to occupancy scenario $5D2S$, for weight categories C and D.

weight category D offers potentially interesting profit margins is confirmed. For scenario *C China* however, although the additional value is positive in 70% of the cases, only in 50% of the cases it is more than 9% of the cost. Scenario *C India* has negative or negligible additional value. In segment C, especially diamonds should be targeted with a high final value per carat.

To gain insight in the relative importance of the different terms of Equation 8.2 in the additional value per carat, the contribution of each term was expressed as a percentage of the cost of polishing with the automatic DPS. Besides transport and capital savings, the outsourcing savings are determined as the cost of outsourcing to China/India minus the cost of polishing with the automatic DPS (i.e. minus 100%). These results are presented as boxplots in Figure 8.40. The four upper boxplots are related to the additional value for segment C, the lower are related to the additional value for segment D. As can be seen from Figure 8.40, if the additional value for C is positive, it is thanks to the savings in transport and capital costs. For D however, polishing with the DPS is in 50% of the cases 10 to 40% cheaper than polishing in China. Polishing in India is in 50% of the cases still 7 to 25% cheaper than polishing with the DPS, but thanks to the substantial transport and capital savings, the additional value is still largely positive. But of course there should be a willingness to pay from the potential customers for these aspects if they are to choose the services of Company δ over the outsourcing to India option.

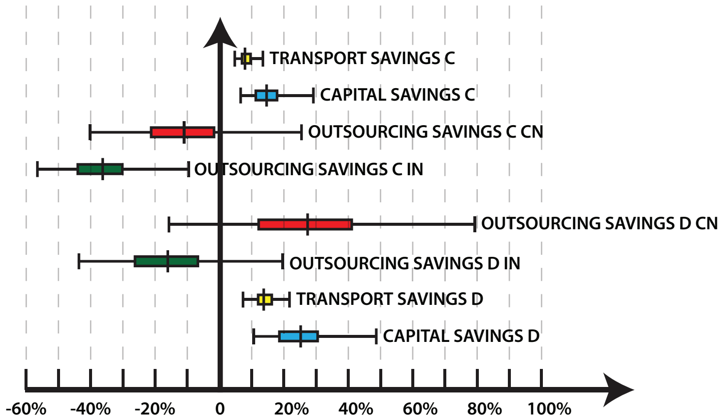

Figure 8.40: Boxplots of the three main components of the additional value versus polishing in China/India for categories C an D, expressed as a percentage of the cost of polishing with the automatic DPS (occupancy scenario $5D2S$).

As already mentioned at the outset of this section, a separate analysis was performed to estimate WTP_{PD}^{max}, the maximum value that can be added by reducing the probability of damaging the stone during polishing. This analysis is presented in Section E.2 of Appendix E. The main conclusion from this analysis is that the maximum additional value through reduction of the probability of damaging the stone is yet another term in Equation 8.2 that depends on the final value of the stone. Naturally, the more valuable the stone is, the graver the consequences of damage are. Depending on the final value per carat, for a C or D tension stone, on average maximally 2 to 6% or 2 to 8% of the polishing cost can be saved respectively, assuming that the probability of damage is reduced to zero.

Validation of the (intermediary) results The model and its input data were validated by presenting preliminary results to the different people involved, such that input parameter estimates and the presentation of output results could be corroborated from independent data sources. Illogical or counter-intuitive results were listed and subjected to further data gathering and model checking efforts. The total number of project team meeting and meetings with external stakeholders, as indicated in Table 2.2, were five and six respectively. Moreover, the results were compared with data and information from industry reports (e.g. [165], [194]).

8.4.5 Step 4: Improvement scenario analysis

The main improvement scenarios related to the DPS have been defined and subsequently analyzed, by looking at their impact on the polishing cost and on the additional value. The discussion is focused on segment D, occupancy scenario $5D2S$ and the variable combination of technical and activity parameters of the DPS. Finally, the conclusions with regards to the business potential of the different PSS options for Case δ are formulated.

Identification of improvement scenarios

The improvement scenarios for Case δ are presented in Table 8.18.

Table 8.18: Improvement scenarios to reduce cost or improve value for Case δ.

Parameter category	**Description of improvement scenario**
technical parameters	*D1*: increasing the lifetime of the polishing disks
	D2: reducing the cost of the polishing disks
	D3: increasing the lifetime of the emulsion
	D4: reducing the investment cost per module
	D5: reducing the probability of damaging a stone in comparison to the manual processing situation
activity parameters	*D6*: reducing the process time of the finishing operation
	D7: reducing the total leadtime of the process
provider parameters	*D8*: increasing the occupancy of the available modules to occupancy scenarios $7D2S$ and $5D3S$

Analysis of improvement scenarios

The results of the quantitative analysis of the improvement scenarios are presented in Table 8.19 (all for segment D).

Table 8.19: The main results of the quantitative analysis of the improvement scenario examples of Table 8.18.

Parameter category	Description of improvement scenario
technical parameters	*D1*: per stone that the lifetime of the polishing disks for finishing is increased, the average cost per carat is reduced by 1,7%
	D2: per 100$ that a polishing disk costs less, the average cost per carat is reduced with 4,7%
	D3: the average cost per carat decreases with 0,57% for each carat that is added to the lifetime of the emulsion (the lifetime is expressed in the number of carats removed)
	D4: reducing the investment cost per module with €10.000 reduces the average polishing cost with 0,6%
	D5: the maximum additional value of reducing the probability of damage is estimated in Section 8.4.4 (cfr. Figures E.4 and E.5)
activity parameters	*D6*: for each minute that the finishing time of one side of a stone is reduced, the average cost per carat is reduced with 0,84%
	D7: for each day that the leadtime can be shortened, in between 0,6–2% of additional value is created, depending on the final value of the stone
provider parameters	*D8*: increasing the occupancy of the available modules to occupancy scenarios $7D2S$ and $5D3S$ reduces the average cost per carat by 5,5% and 6,3% respectively.

Conclusions for Case δ

In Table 8.20, the improvement scenarios are linked to PSS options $PSS_{\delta 1}$ to $PSS_{\delta 5}$ (represented in Figure 6.3 and described in Table 6.3) in a similar way as was done in Sections 8.1.5, 8.2.5 and 8.3.5. The crosses indicate a direct link between the realization of a specific improvement scenario and the revenues and costs of Company δ.

Table 8.20: Matrix linking the improvement scenarios $D1$ to $D8$ of Table 8.18 with the five PSS options for Company δ.

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
$PSS_{\delta 1}$	X	X	X	X	(X)	X		X
$PSS_{\delta 2}$	X	X	X	X	(X)	X		X
$PSS_{\delta 3}$				X				
$PSS_{\delta 4}$				X				
$PSS_{\delta 5}$	X	X	X	X	X	X	X	X

The majority of the improvement scenarios will only result in a direct reduction of costs or a direct increase of revenues for Company δ if one of the performance oriented PSS types $PSS_{\delta 1}$, $PSS_{\delta 2}$ or $PSS_{\delta 5}$ is adopted. Only if Company δ adopts $PSS_{\delta 5}$ and thus becomes the owner of the stones it is processing, the improvement scenarios related to the leadtime and the damage to the stones will result in direct financial benefits[23].

For various reasons, the feasibility of $PSS_{\delta 5}$ is inhibited. In the diamond gemstone industry, stable access to raw material is restricted to so-called 'sightholders' and mainly depends on the ability of diamond processing companies to negotiate long term contracts with one or more of the major producers [194]. Moreover, because of the specific context in which the GIP technology has been developed, with different stakeholders involved, $PSS_{\delta 5}$ was not seen as a realistic option.

Both the complete *diamond processing service* ($PSS_{\delta 1}$) and the *diamond polishing service* ($PSS_{\delta 2}$) allow to tap the innovation potential of the majority of the improvement scenarios in Table 8.20. Both allow to protect the central technology from IPR infringement, a risk that is higher for PSS options $PSS_{\delta 3}$ and $PSS_{\delta 4}$. The choice between $PSS_{\delta 1}$ and $PSS_{\delta 2}$ should take into account the following aspects:

- The investment requirements for $PSS_{\delta 1}$ are larger, because also equipment for planning and sawing should be purchased. More skilled workers should be hired, that are able to execute all of these steps.
- As explained in Section 8.4.4, planning is a critical step in the process chain of a diamond processing company. Whether the potential customers of a diamond processing center would be inclined to outsource the responsibility for planning is not at all certain. Moreover, the company that is operating the diamond processing center should have the expertise for planning. Possibly, a hybrid offering (cfr. Section 6.4) could be developed with an external partner that is specialized in the planning step.
- The main advantages of $PSS_{\delta 1}$ over $PSS_{\delta 2}$ are related to the following value aspects for the customer: convenience (for a diamond processing company, the complexity of coordinating one batch of diamonds is reduced), responsiveness (if all process steps are performed by one actor in one location, the total leadtime of the process could be reduced, thereby reducing the capital costs) and, potentially, accuracy (if sufficient expertise for planning is available).

During discussions with the central project team of Company δ, taking into account all aspects mentioned, $PSS_{\delta 2}$ emerged as the most realistic and

[23] Unless if Company δ would become financially liable for the value lost when its customer's tension stones are damaged. Therefore, the crosses at scenario D_5 are put between brackets.

interesting PSS option. As demonstrated in Section 8.4.4, the additional value of an automatic DPS is the largest for segment D. Besides the technical and activity parameters that drive the cost of the automatic DPS and that are represented in Table 8.18, the additional value also depends on characteristics of the stone that is polished. The following indicators allow to identify the stones within segment D that have a maximal additional value:

- Stones with a high final weight
- Stones with a high final value per carat
- Stones with a low recovery weight[24]
- Stones that are currently outsourced to China are more interesting than those outsourced to India

Overall, as we have seen in Section 8.4.4, for the largest share of segment D, there is a positive additional value of the automatic DPS. But, as we have seen in Figure 8.40, for stones outsourced to India, this additional value is only appreciated if customers are willing to pay for a reduction of transport and capital costs. The outsourcing savings that are determined by only comparing the polishing costs are only positive in the majority of the cases versus China. More value could be added if the probability of damaging the stones can be reduced (cfr. Appendix E).

For segment C, as we have seen in Figure 8.39, the additional value can be in between -39% and 30% of the new polishing cost, and depends on the same factors as indicated for segment D. Here, only the stones that are currently outsourced to China have a sufficient profitability potential (cfr. Figure 8.39). Other conditions such that the additional value of an automatic DPS is larger than 10% of the polishing cost are described in Section E.2 of Appendix E.

Generic conclusions

The following *generic conclusions* can be derived from application of the methodology of Chapter 7 for Case δ:

- Validation of input parameter estimates from different, independent sources is crucial to come to robust and credible conclusions, especially if expert opinions are an important source of information. The main information sources in this case were external, especially for parameters that are instrumental in quantifying the value impact.

[24]This is not in contradiction with the first condition, but rather suggests that for two stones with the same final weight and the same value per carat, the additional value of polishing with the DPS is maximal if the recovery weight or yield of the initial stone is lower.

- In this case, it has proven crucial to choose either distributions to represent the uncertainty of specific input parameters or to determine a set of scenarios on some key variables in order to derive useful conclusions and enhance the interpretability of the results. Deciding which parameters will be chosen to discern scenarios should be done pragmatically and ad hoc, based on the different decisions that can be taken through application of the quantitative method. For example, it is far more informative to discern four different weight categories for the diamonds between 0,25 and 1,00 ct than to apply a single distribution, because this will have a large impact on the results. Likewise, it is far more informative to distinguish the four occupancy scenarios than to include occupancy as a single statistically distributed parameter within the simulation model. Thirdly, the optimistic, pessimistic and most likely scenarios for the GIP process parameters can illustrate the effect of a global optimization of the GIP process design.

- The presented case study illustrates how Value quantification strategy 4 can be applied in practice, i.e. by quantifying the additional value over the price of a competing offering. Company δ representatives indicated that being able to quantify the value in relation to a competing offering leads to more practically relevant insights than a quantification of absolute value. Thus, this case suggests that if a competing offering can be identified, Value quantification strategies 3 or 4 are preferable over 1 or 2.

- One of the major outcomes of this case for Company δ is that the presented approach allows to identify the market segments for which the value of a DPS is optimal. At the outset of this study, it was not known for which types of diamonds (e.g. which weight categories) the GIP technology should be tailored.

- The presented study shows how the methodology of Chapter 7 can steer R&D professionals towards the optimization of technical parameters with the largest effect on the business potential of the technology they are developing. Therefore, application of this kind of analysis should preferably be carried out early in R&D projects, where there are still more degrees of freedom in focusing R&D attention.

8.5 Case λ: Wind turbine gearboxes

This section summarizes a case study performed for a manufacturer of wind turbine gearboxes, which was carried out as a master thesis project in the Master of Industrial Management program at KU Leuven [18, 220]. The main objective of this study was to quantify the additional value of implementing a condition monitoring system (CMS) on a gearbox. Although the focus was not on analyzing the innovation potential of a PSS, this case can be seen as the analysis of one particular improvement scenario: the implementation of a condition monitoring system and a condition-based maintenance policy. Several authors have highlighted the role of CMSs as enablers of PSS models [7, 78, 135], and therefore the analysis of this improvement scenario is seen as particularly relevant.

In the previous sections, each case was presented in its entirety, but this section only discusses some notable aspects of Case λ related to certain steps of the methodology of Chapter 7.

8.5.1 Background: condition monitoring for wind turbine gearboxes

A suitable maintenance policy for wind turbines should cope with several challenges. On the one hand, spare parts are costly. On the other hand, the accessibility of the main components is hampered by the requirement to use cranes and by the dependency on weather conditions. Failures of the gearbox are one of the main reasons for malfunctions of wind turbines [193]. A CMS could help to overcome unexpected downtime and reduce costs by providing timely information on failures that have occured or are about to occur and by preventing consequential damage to other parts. A gearbox CMS operates according to one or more of the following working principles: vibration monitoring, lubrication oil analysis, ultrasonic measurement and thermographic analysis.

Company λ, a manufacturer of gearboxes, currently has a corrective and preventive maintenance policy (policy A) but is interested in implementing a combination of corrective, time-based preventive and condition based maintenance (policy B). The goal of the presented case study is to compare policies A and B. Although CMSs have proven their worth in other industries, a gearbox in a wind turbine application is not comparable with any other industrial gearbox application. The variability of the wind regime and its concurring load spectrum make the wear and deterioration behavior difficult to predict [18]. Therefore, being able to model the imperfect performance of the CMS was identified as critical in this case.

8.5.2 Step 1: Goal and scope definition

The goal of Case λ is the quantification of the additional value of a CMS, or, in other words, of maintenance policy B over policy A (cfr. Section 8.5.1). One particular type of gearbox was chosen for which this analysis was performed.

The additional value of the CMS is determined by its economic impact on the operation and maintenance of the wind turbine, which is expressed by the performance indicators listed in Table 8.21.

Table 8.21: Value components and corresponding performance indicators for a wind turbine gearbox CMS (Case λ). The indicators displayed in bold were chosen for further analysis.

Value aspects	Value components	Performance indicators
Responsiveness	Responsiveness to failures	• **Effect on diagnosis time** [%]
Flexibility	Ability to facilitate external cost savings or revenue increase	• **Effect on crane rental costs** [€] • **Effect on spare part costs (i.e. reduction of inventory level)** [€] • Effect on downtime claims by turbine owners [€] • **Effect on lost energy production** [€] • **Effect on corrective and preventive maintenance costs (including avoided consequential damage)** [€]
Productivity	Maintainability	• **Effect on repair time** [%] • **Effect on time-based maintenance interval** [%]
	Accuracy	• **Cost of false alarms** [€]

8.5.3 Step 2: Model development

In this section, only some noteworthy modeling choices are discussed: the modeling of the imperfect performance of the CMS, the modeling of the deterioration behavior and the quantification of certain performance indicators of Table 8.21.

Modeling of the CMS performance and the deterioration process Through discussions with representatives of Company λ, in total 13 failures of a wind turbine gearbox were identified. As will be elaborated in Section 8.5.4, 6 out of these 13 failure modes were included in the model, because they were identified as the dominant failures modes according to a cost-based FMEA.

The deterioration process was modeled based on the *P-F curve* (cfr. Figure 8.41), a visualization of the deterioration over time of a component [149]. The point 'F' of this curve corresponds to a functional failure of the component and the point 'P' corresponds to the point in time when the deterioration can be detected. The *P-F interval* is the time period in between P and F.

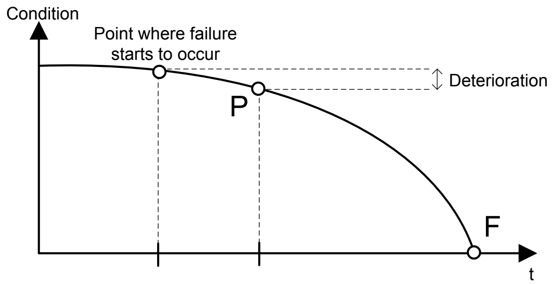

Figure 8.41: P-F curve [18, 220].

The *imperfect performance of the CMS* is modeled by introducing two parameters: the *detectability* γ (the probability that a failure is detected by the CMS) and the *efficiency* η (the spot on the P-F curve where the failure is detected by the CMS). The relation γ and η can be defined by a curve, for example a linear one such as in Figure 8.42b. From this figure, it can be seen that the detectability γ increases with rising efficiency, which is an expected dependence of both parameters.

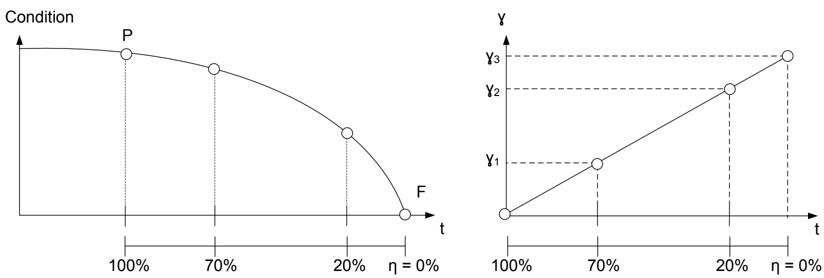

Figure 8.42: (a) Representation of the CMS efficiency η on the P-F curve. (b) Relation between CMS efficiency η and detectability γ [18, 220].

For each failure mode, the relation between γ and η can be defined, and this relation corresponds to the ability of the CMS to detect that particular failure. In Figure 8.42, $\eta = 100\%$ corresponds to detection in the earliest possible point and $\eta = 0\%$ corresponds to detection when there is already a functional failure. For example, the pair ($\gamma_1 = 20\%$, $\eta = 70\%$) means that the CMS is on average able to detect 20% of the developing failures at 70% remaining life between P and F. In the presented case, since no detailed information was available on the relation between γ and η, a simplified version of this model was implemented. For each failure mode, one pair (γ, η) was specified to model the CMS's imperfect performance.

The *deterioration behavior* can be modeled by dividing the P-F curve into four deterioration zones (Figure 8.43), each of which corresponds to a different repair action:

- *Zone A* corresponds to an early stage deterioration with limited component damage. Repair actions are restricted to minor adjustments on site.
- *Zone B* corresponds to significant component damage without consequential damage. Only one component needs to be repaired or replaced.
- *Zone C* corresponds to maximal component damage, but the gearbox is still running. Consequential damage is possible.
- *Point F* corresponds to full functional failure and downtime of the gearbox. Also in this case, consequential damage is possible.

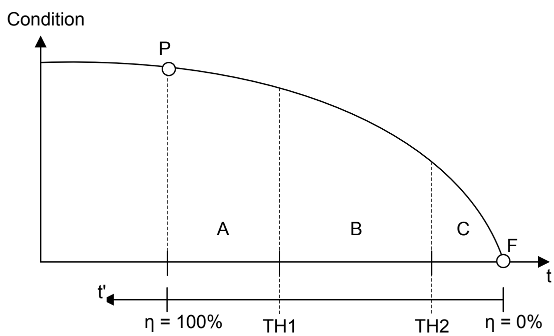

Figure 8.43: P-F curve divided into deterioration zones [18, 220].

The zones of the P-F curve are separated by threshold values $TH1$ and $TH2$, that are a characteristic of that particular failure mode. Figure 8.43 illustrates that depending on the CMS's efficiency η, the failure can be detected in one of these zones. The starting point on the timeline t' indicates the residual useful life of the component. If $TH1 = 20\%$ and $\eta = 95\%$, the failure could be detected in zone A. If $TH1 = 80\%$, $TH2 = 60\%$ and $\eta = 40\%$, the failure is detected only in zone C. Treshold $TH2$ defines the moment in time from which consequential damage to other components can occur.

Thus, by specifying for each failure mode the parameters $TH1$ and $TH2$ and for each type of CMS a pair (γ, η), per failure mode, the failure behavior and imperfect operation of the CMS can be modeled.

Value quantification The quantification of value was performed by expressing each performance indicator as a maximum WTP, thus through application of Strategy 2 of Section 7.3.1. This maximum WTP was determined by quantifying the economic impact of each indicator, i.e. the cost savings that can be realized through maintenance policy B over the *business as usual* scenario (policy A).

The most important performance indicator of Table 8.21 is the *effect on corrective and preventive maintenance costs (including avoided consequential damage)*, which was determined through application of the modeling logic for the CMS's imperfect performance and for the deterioration behavior of the gearbox. The calculation is detailed in [18, 220]. For some of the other performance indicators, a set of β-parameters was introduced:

- *Effect on diagnosis time - β_{1i}*: Naturally, a CMS is expected to lead to a reduction of the time necessary to point out the relevant failure mode. This is modeled by introducing a failure-mode specific parameter β_{1i}:

$$\beta_{1i} = \frac{TTD_{iB}}{TTD_{iA}} \tag{8.4}$$

  TTD_{iA} is the time-to-diagnose for a failure on FM_i in maintenance policy A and TTD_{iB} is the time-to-diagnose for a failure on FM_i in maintenance policy B.

- *Effect on spare parts stock level - β_{2i}:* A failure that is detected by the CMS before evolving into a functional failure creates the opportunity to keep the gearbox running while the appropriate components are on order. Therefore, the stock level can be reduced without increasing the risk for running out of spare parts. This effect is modeled by parameter β_{2i}:

$$\beta_{2i} = \frac{K_{iB\,CM_{spp\ stock}}}{K_{iA\,CM_{spp\ stock}}} \tag{8.5}$$

  $K_{iA\,CM\ spp\ stock}$ is the stock level of spare parts for failure mode FM_i in policy A and $K_{iB\,CM\ spp\ stock}$ is the stock level of spare parts for failure mode FM_i in policy B.

- *Effect on time-based maintenance interval - β_{3i}:* When a CMS is available, the interval for performing time-based maintenance can be extended, because unnecessary preventive inspections are rendered unnecessary the CMS. This effect is modeled by parameter β_{3i}:

$$\beta_{3i} = \frac{T_{B\ interval}}{T_{A\ interval}} \tag{8.6}$$

$T_{A\ interval}$ is the time between two successive time-based maintenance interventions in policy A and $T_{B\ interval}$ is the time between two successive interventions in policy B.

- *Effect on repair time - β_{4i}:* If a failure is detected in an 'earlier' zone of the P-F curve (cfr. Figure 8.43), it requires a repair that in general takes less time. This effect is modeled by parameter β_{4i}:

$$\beta_{4i} = \frac{TTR_{iB}}{TTR_{iAz}} \tag{8.7}$$

TTR_{iA} is the time to repair failure mode FM_i in policy A and TTR_{iBz} is the time to repair failure mode FM_i in policy B when the failure is detected in zone z, where z equals A, B, C or F (cfr. Figure 8.43).

Thus, by modelling a set of parameters that can be estimated by eliciting expert opinions both internally (experts from Company λ) and externally (experts from CMS providers), a quantification of the corresponding value aspects can be derived.

8.5.4 Step 3: Data gathering, output analysis and model validation

In this section, one aspect related to the data gathering in Case λ is highlighted: how cost-based FMEA can be applied to identify the main failure modes of a system.

Failure modes and effects analysis (FMEA) is a widely applied method to determine the most critical failure modes of equipment. In traditional FMEA, for each failure mode a risk priority number (RPN) [5] is determined as the product of three subjective estimates, reflecting the occurence, severity and occurence of each failure mode. The main disadvantage of this method is its dependency on subjective estimates [197]. An alternative is *cost-based FMEA* [170], whereby risk is measured in terms of the total estimated failure cost, which is defined by the following equation:

$$Total\ estimated\ failure\ cost = \sum_{1}^{n} p_i \times c_i \tag{8.8}$$

In Equation 8.8 p_i is the probability of occurrence of failure mode i, c_i is the associated cost with failure mode i and n is the total number of failure modes. The probability of failure can be determined by analyzing the actual number of field failures that occur within a specified time window. The failure cost consists of labour cost, material cost and downtime cost. The main advantage of cost-based FMEA over traditional FMEA is its use of an objective measurable parameter to estimate the risk associated with a failure mode.

Through application of both traditional FMEA and cost-based FMEA, the ranking of failure modes for a particular wind turbine gearbox was determined. For the traditional RPN calculation, a cross functional team of Company λ representatives supplied the estimates for all parameters, while rough estimates for the cost-based FMEA were determined by analyzing historical failure data. The ranking of failure modes according to the total estimated failure cost derived by application of cost-based FMEA is presented in Table 8.22.

Table 8.22: The failure modes of a gearbox population, ranked by their total estimated failure cost (through application of cost-based FMEA) [18].

	Failure mode	Failure cost (€)
1	High speed shaft bearing failure	10,207,393
2	Broken intermediate shaft	7,797,154
3	Intermediate shaft bearing failure	3,701,940
4	Planet bearing failure	3,515,432
5	Broken centre post	2,296,527
6	High speed shaft bearing black spot	1,999,723
7	Sun gear - broken teeth	1,951,066
8	Low speed shaft bearing failure	1,833,967
9	Intermediate shaft bearing failure	1,764,277
10	High speed shaft grinding temper failure	843,824
11	Broken low speed wheel	441,526
12	Oil pump failure	308,491
13	Intermediate shaft splash plate failure	90,858

In Table 8.23, 6 of the 13 failure modes account for 80% of the total estimated failure cost. Only these failure modes were retained.

The ranking according to traditional FMEA displayed significant differences from that determined through cost-based FMEA. A comparison of both rankings is provided in Table 8.23. All participants in the case study, including Company λ representatives, expressed more confidence in the ranking obtained through cost-based FMEA because it was based on objective historical data, as opposed to RPN-based FMEA which is founded solely on subjective estimates and does not include actual failure information. Therefore, this case suggests that traditional FMEA should be used with great care for identifying the main failure modes of a product, and that cost-based FMEA should be preferred if historical data are present.

Table 8.23: Comparison of the ranking of failure modes according to traditional and cost-based FMEA [18].

Rank according to traditional FMEA	1	2	3	4	5	6	7	8	9	10	11	12	13
Rank according to cost-based FMEA	8	11	12	6	13	4	7	2	5	1	3	9	10

8.5.5 Step 4: Improvement scenario analysis

As this case corresponds to the analysis of one particular improvement scenario (the introduction of a CMS), this section presents some results on the analysis of the value improvement potential of this scenario. Extensive output analyses are presented in [18] and [219]. Here, only the analysis of the influence of the CMS performance on the additional value of maintenance policy B over policy A is presented.

Figure 8.44 illustrates the effect of the two CMS performance parameters γ_i (detectability) and η_i (efficiency) on the additional value of a CMS. The effect of γ_i is analyzed while keeping all η_i's at a deterministic value, determined through expert opinion. As a simplification, no distinction is made in CMS detectability between the failure modes ($\gamma_i = \gamma_1 = \ldots = \gamma_6$). Similarly, the influence of η_i is analyzed by keeping all η_i's at a deterministic value. At all times the threshold values $TH1_i$ and $TH2_i$ are kept constant at respectively 90% and 15%.

The average additional value of policy B over policy A increases linearly with increasing γ_i and becomes positive at $\gamma_i = 19.5\%$. The average additional value of policy B over policy A shows a discontinuous function with increasing η_i. The discontinuous character is caused by the threshold values $TH1_i$ and $TH2_i$, which are set at 90% and 15%. The created levels in the graph correspond to the deterioration zones (cfr. Figure 8.43). For the values of $\eta_i < 15\%$ (detection in zone C or point F), implementation of a CMS into a gearbox of an onshore wind turbine is not justified.

This sensitivity analysis demonstrates that it is crucial to take the CMS performance into account when determining its additional value.

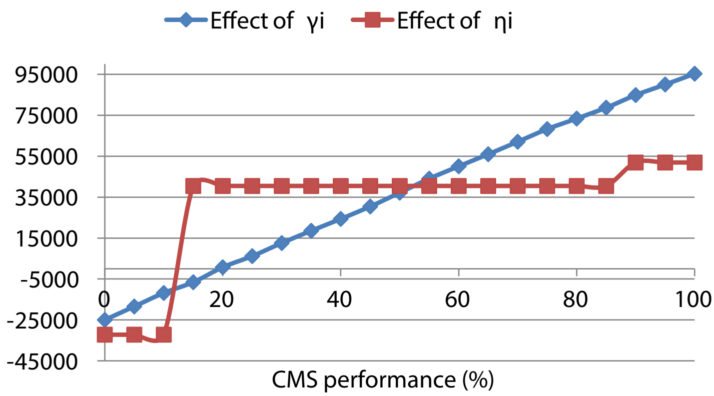

Figure 8.44: Evolution of the average additional value of policy B over policy A (in €) as a function of γ_i and η_i [18, 220].

Generic conclusions

The *generic conclusions* related to Case λ are the following:

- The imperfect performance of a CMS can be modeled through the approach described in Section 8.5.3, by introducing efficiency and detectability parameters per failure mode, that depend on the specific type of CMS applied. Through a sensitivity analysis, as for example the one presented in Section 8.5.5, the minimal detectability and efficiency of a CMS can be determined such that a CMS incurs an additional value.
- By introducing tresholds $TH1$ and $TH2$ and dividing the P-F curve into four zones A, B, C and F, the deterioration behavior of particular failure mode can be modeled, taking into account different repair actions that are required and the possibility of consequential damage.
- For certain value aspects, the additional value can be quantified by introducing a set of parameters such as the β-parameters of Section 8.5.3. These express the influence of a CMS on some key value aspects and can be determined by eliciting expert opinion.
- Identifying and ranking the most important failure modes can be done by applying either traditional (RPN-based) FMEA or cost-based FMEA. As demonstrated in Section 8.5.4, both rankings can differ significantly. In the presented case cost-based FMEA was seen as a superior method because it relies less on subjective estimates as traditional FMEA.

8.6 Cross case analysis and validation

In Chapter 7, a generic methodology is presented to evaluate the innovation potential of a PSS in value improvement and cost reduction. The case studies presented in this chapter highlight a wide variety of generic methodological aspects and propose practical approaches to tackle them. They are summarized in Section 8.6.1. In Section 8.6.2, we argue that the presented cases serve as a validation of the methodology of Chapter 7, by demonstrating its applicability in various contexts.

8.6.1 Cross case analysis

The main characteristics and specific methodological aspects of the cases are summarized in Table 8.24. This table shows that each case adds complementary insights, as they differ in several key aspects (e.g. value quantification strategy, main focus of the cost analysis, dominant mechanisms). Although Table 8.24 is the most appropriate visualization of the complementarity of the various cases, the defining features and peculiarities of each case in relation to the others are discussed in the following paragraphs.

Case α (elevators) is focused on the cost and value improvement potential during the use phase of an investment good that consists of a central, standardized product. The main potential of a PSS is related to an improvement of activity, technical and logistical parameters that allow to reduce the maintenance cost, downtime and number of failures. A specific issue encountered is the abscence of reliable internal historical data, which can be dealt with by eliciting and validating expert opinions and information from external sources (e.g. number of travel cycles). The value of an elevator is a multidimensional set of non-monetary performance indicators, for which the expression into a single monetary measure (maximum WTP) was not seen to result in additional insights. Therefore, Value quantification strategy 1 was chosen.

Case β (lighting control systems) is focused on the initial labor related costs and on the value during the use phase, expressed in monetary terms, of a decentralized system that can be highly customized. In contrast to Case α, the value of an LCS is largely determined by one performance indicator in particular: the ability of an LCS to reduce the lighting energy costs in a building. For the performance based PSS types, the business potential of a PSS depends on the one hand on its ability to expand the customer base (through Mechanism 4) and on the other hand on the value of the LCS. This value is driven mainly by customer specific parameters and thus Case β exemplifies how to identify the key parameters that correspond to promising market subsegments for a PSS.

Table 8.24: Main characteristics and methodological aspects of the five cases described in Chapter 8.

Case	**Evaluation basis**	**Main information sources**	**Value quantification strategy**	**Main focus of the cost analysis**	**Specific methodological issues and focus**	**Dominant mechanisms (Section 3.4.1)**
α	solution-centric result	internal expert knowledge, measurements	Strategy 1 (non-monetary)	use phase (maintenance, energy, logistics)	• modeling of failure modes (repairs, diagnosis, logistical aspects) • eliciting and validating expert opinions • identification and analysis of many improvement scenarios related to technical, logistical and activity parameters	Mechanisms 1, 2
β	environment-centric and solution-centric result	internal expert knowledge, literature	Strategy 2 (monetary)	initial labor related costs	• taking into account quality factors that influence the time to perform activities • focus on the identification of market subsegments for which the value potential is maximal • dealing with different functional results for different PSS types and customer subsegments (recent vs. old offices)	Mechanisms 2, 4
γ	solution-centric result	internal expert knowledge, historical data	Strategy 1 (non-monetary, limited focus)	production and use phase	• modeling the cost of a highly customized and complex technical environment, consisting of different component types • choosing the appropriate cost object • validating cost estimates through comparison with accounting data • analysis of renovation scenarios	Mechanisms 1, 3, 4
δ	demand fulfillment and environment centric result	external and internal expert knowledge	Strategy 4 (monetary additional value versus a competing offering)	use phase (consumables, operation)	• identifying the key technical parameters of a product that is still under development • eliciting information from (potential) customers • identifying market subsegments for which the value potential is maximal • taking into account the price of a competing offering • choosing parameters for discerning scenarios	Mechanisms 1, 2
λ	solution-centric result	historical data, internal and external expert knowledge	Strategy 2 (monetary)	use phase (maintenance, logistics)	• applying cost based FMEA for identifying most important failures modes • analyzing the additional value of a CMS, taking into account its imperfect operation • modeling a deterioration process with different zones • modeling the impact of a CMS on various value aspects	Mechanism 2

As discussed in Section 8.2, Case β illustrates that the analysis of various PSS options can necessitate the introduction of a separate evaluation basis.

At first sight, *Case* γ (fire detection systems) investigates a similar type of product as Case β: a highly customized, decentralized system consisting of a variety of nodes and control units. However, in Case γ, the potential of a PSS is more related to Mechanism 1 (cost reduction), whereby the costs during the production and use phase are dominant. Deriving a detailed quantification of the key performance indicators of an FDS's value has been proven to be impeded by the abscence of reliable fire safety statistics. But the cost improvement potential of a PSS was analyzed in detail. Together with a PSS's influence on the competitive environment (Mechanism 3) and on the expansion of the customer base (Mechanism 4), this cost reduction potential (Mechanism 1) was shown to be dominant for the business potential of a PSS. As for Case β, although Mechanisms 3 and 4 are not included in the quantification approach (i.e. estimates of price and the expansion of the customer base are not derived), the methodology's usefulness has been attested for identifying the key profitability indicators of a PSS.

Similar to Case α, *Case* δ (diamond polishing systems) is concerned with a central product. But unlike an elevator, an automatic DPS is a very immature technology, i.e. one that is still under development. Case δ is characterized by many uncertainties related to the technical parameters of the DPS, and as demonstrated in Section 8.4, application of the methodology allows to identify the parameters that have the largest influence on the profitability of a PSS. Stochastic simulation in combination with scenario analysis helps to identify the most important characteristics of the stone that determine the additional value of the new polishing technique. Besides, the overall improvement potential that can be gained from optimizing technical parameters is assessed and thus R&D professionals can be steered towards the optimization of technical parameters with the largest effect on the business potential of the technology they are developing.

Finally, *Case* λ (wind turbine gearboxes) provides an illustration on how the additional value of one particular improvement scenario, namely the implementation of a condition monitoring system (CMS), can be analyzed. A novel approach was presented to model the CMS's imperfect performance and to model the deterioration process by dividing the PF-durve in different zones and by taking into account variable failure impacts based on the point in time when the failure is detected. This approach has generic relevance, given the fact that several authors identify CMSs to be enablers of a PSS model (cfr. Section 8.5).

In the different cases, appropriately dealing with uncertainties and risks has proven to be crucial and insightful. Uncertainty is only introduced for parameters that cannot be determined with certainty with a reasonable effort. But, as in each case typically many different input parameters are to be estimated, deriving accurate estimates is not always possible or advisable. More accurate estimates of the time to perform certain activities could for example be derived through time studies, but if tens or even hundreds of activities occur over the lifecycle of an investment good, some of which only occassionaly, substantial efforts are required to obtain them. By introducing uncertainty distributions in the model for these parameters, their impact on the output variation can be assessed and thus extra data gathering efforts can be guided, thereby making the application of the methodology more efficient.

Aleatory uncertainties cannot be reduced through further study and should reflect reality. In each of the cases, this type of uncertainty is encountered, e.g. the number of travel cycles of an elevator, the dimensions of the office in which a lighting control system or a fire detection system is installed, the price per carat of various diamonds, etc. Taking these aleatory uncertainties into account is necessary to achieve a cost and value estimate that is representative for the whole segment under study.

For each of the presented cases, a significant variation in the cost and value outputs is encountered and taking into account uncertainties and risks was proven to be useful. The main advantages of their inclusion are that realistic and representative cost and value outputs can be determined and that important parameters that drive the output variation can be identified. However, the added value of modeling uncertainties and risks varies per case. For case γ, the uncertainty in the model needed to be reduced, sacrificing representativeness for relevancy: not all possible combinations of different nodes (detectors, sirens,. . .) could be included in the model, otherwise these application specific input parameters would blur the influence on the output variation of other input parameters that are more under the company's control (e.g. activity and technical parameters). Specifically in case δ, the large uncertainties for technical parameters and stone specific parameters, warranted a thoughtful combination of scenarios and distributions. By doing this, crucial insights were derived on the most attractive market segments and on the dominant technical parameters.

8.6.2 Validation of the methodology

As indicated in Section 3.4.2, no alternative approach is available that allows to quantify the *PSS innovation potential* in cost reduction and value improvement ex ante, taking into account all relevant *risks and uncertainties*. Therefore, the performance of the presented methodology cannot be compared with equivalent approaches. However, by analyzing the case studies that were performed, one can judge whether these specific requirements (the focus on the innovation potential and the inclusion of uncertainties and risks) were proven to be justified:

- For each case, in the step 'improvement scenario analysis', a *substantial PSS innovation potential* was identified. Although only Mechanisms 1 and 2 are included in the assessment, even in cases were Mechanisms 3 and/or 4 contribute to the business potential of a PSS, the usefulness of the methodology was attested. The specific improvement scenarios and their impact was shown to be highly case-specific, but the generic method of analyzing these scenarios and linking them to the PSS options of Chapter 6, allowed to derive meaningful conclusions for each case.
- In each case, the *stochastic approach*, applied to account for uncertainties and risks, was shown to be necessary and useful. By combining Monte Carlo simulation and scenario analysis, the key determinants of the cost and value potential of a PSS can be identified; the market segments that promise to be the most attractive for a particular PSS option and the dominant technical or operational parameters that determine its profitability.

The fact that case studies were selected as a method to validate the methodology of Chapter 7, is logical, given the nature of the research questions (which are essentially *how* questions, cfr. Chapters 1 and 2) and given the observation that the drivers, barriers and opportunities for companies to shift to a PSS are known to be highly context-specific [144]. This observation is confirmed in the presented case studies. Even if only Mechanisms 1 and 2 are considered, the business potential of a PSS is highly context- and case-specific. Several contextual factors were identified that influence the feasibility of a specific PSS option (e.g. the willingness to outsource planning in Case δ, the building codes in Case γ). For each case, the business potential was found to depend on a specific set of improvement scenarios. Even a similar improvement scenario can have a very different impact depending on the particular case for which it is considered (e.g. the opportunistic maintenance scenarios $A7$ and $C4$ for Cases α and γ).

The appropriate method to assess the value-in-use of an investment good was found to be highly case-specific. Despite this specificity, in each case a generic decomposition of value aspects could be applied and one of four generic value quantification strategies could be selected. Except for Strategy 3 of Section 7.3, the application of all Value quantification strategies of Chapter 7 was illustrated: Strategy 1 in Case α, Strategy 2 in Cases β and λ and Strategy 4 in Case δ. In analogy to the relation between Strategy 1 and 2, Strategy 4 is an extension of

Strategy 3: it does not only quantify non-monetary performance indicators (e.g. leadtime in days) but also transforms these into maximum WTP (e.g. leadtime in capital costs). Therefore, the application of Strategy 3 is a straightforward combination of that of Strategies 1 and 4, demonstrated in Cases α and δ.

As a general conclusion for the value analysis, the presented cases suggest that Strategies 1 and 3 are preferable over a monetary quantification, through Strategies 2 and 4, if, for a particular improvement of a performance indicator, the maximum WTP is highly customer-specific and if the actual WTP is only a fraction of the maximum WTP. If these conditions do not apply, a monetary quantification is seen as superior, as this allows to quantify the maximum provider surplus, which is an upper limit of the potential profitability of a PSS, as was demonstrated in Cases β, δ and λ. If there is a competing offering, Strategies 3 and 4 are preferable over Strategies 1 and 2, because they allow to consider only the 'value differences' between the investment good and its alternative. The additional value thus determined over the price of the competing offering, will be closer to the price than the absolute value and thus allows for a more accurate approximation of the provider surplus (cfr. Figure 7.3).

Another aspect that is highly case-specific, is the time necessary to apply the proposed methodology, which was found to depend on the number of input parameters of the simulation model (determined by the type of product and the number cost and value components included in the analysis), the total time period over which the analysis was performed (whereby a shorter period increases the efficiency) and the quality of expert estimates (that determines the number of iterations necessary to achieve the validation of the underlying simulation model).

Although case studies as a research method are inherently limited in the extent to which findings can be generalised [9], the presented cases indicate that the methodology of Chapter 7 has a wide applicability. For cases α, β, γ and δ, it allowed to assess all PSS options that resulted from PSS ideation (cfr. Chapter 6) in terms of their cost and value potential. As demonstrated throughout this chapter, in each case, the desired level of accuracy was achieved[25], and important insights were derived that were not present at the outset of each case (cfr. generic conclusions in Sections 8.1, 8.2, 8.3 and 8.4). On the other hand, as elaborated in Chapter 2, the cases were selected such that they are representative for a large share of the target group of the methodology, manufacturers of investment goods. This representativeness can be judged based on the characteristics provided in Table 2.3. Each case is comprehensively described, in this chapter and in Appendices B to E, to enhance the methodological rigor of the case study research, which depends on its quality in three dimensions: transferability,

[25] Except for the value analysis of Case γ, cfr. Section 8.3.

truth-value and traceability. The measures taken to safeguard these three quality aspects are summarized in Table 2.4.

8.7 Conclusions

In this chapter, five case studies were presented to demonstrate the applicability of the methodology of Chapter 7. As indicated in Sections 1.1 and 3.4.2, the transferability of many existing PSS evaluation approaches is hampered by a limited verification on in-depth case studies. This chapter described five cases of industrial companies that currently have a product-centric business model but that are interested in analyzing the potential of a PSS. By application of the methodology of Chapter 7, an insight is gained in the economic benefits of various PSS options, focusing on their innovation potential in cost and value. Based on a generic structure of four steps, various improvement scenarios that impact the cost and value per functional result of the investment good were linked to the PSS options derived in Chapter 6.

In combination with the case research design and process description in Chapter 2, sufficient information was provided in this chapter to ensure the transferability, truth-value and traceability of the presented research. Based on the characteristics shown in Tables 2.3 and 8.24, it can be seen that a large diversity of cases has been included in this chapter, such that a significant share of the target group of the methodology of Chapter 7 is represented. As demonstrated in Section 8.6, the presented case studies highlight a wide variety of generic methodological aspects, propose practical approaches to tackle them and serve as a validation of the methodology of Chapter 7, by demonstrating its applicability in various contexts.

Chapter 9

Conclusion

This final chapter summarizes and discusses the main contributions of this thesis and presents opportunities for future research.

9.1 Summary and discussion

The overarching goal of the presented research was to analyze the business potential of a Product–Service System (PSS) for a company that currently manufactures investment goods in a product-centric business model. Logical first questions to be answered were ‘how can a PSS be defined?’ and ‘which types of PSSs can be discerned?’ Based on a critical literature review, we concluded in the first chapters that the PSS research field needs a sound theoretical basis, because the most commonly cited PSS definitions and the classical PSS typology are prone to various problems, as explained in Section 3.2.

Partly, these problems are related to the abscence of a systematic treatment of the concept ‘function’ in the PSS literature, although an orientation towards the provision of function is seen as an essential characteristic of the PSS concept. Chapter 4 presented a novel theoretical framework, *Functional Hierarchy Modeling (FHM)*, that allows to represent the functions of an investment good on different levels of abstraction (*contribution* C_1). In essence, FHM clarifies the link between a system and its overall objective, that consists of one or more core customer demands. The system’s functions are expressed on different levels of abstraction through a means-end decomposition. With every level of abstraction, a functional result can be associated, and the full hierarchical model clarifies which other products, services and processes contribute to the attainment of performance at a particular level of abstraction. Besides explaining the theoretical foundation of FHM, Chapter 4 demonstrated how an FHM can be constructed. The chapter ended by discussing the types of innovation opportunities identifiable within this model.

In Chapter 5, a Product–Service System was defined as "*an integrated offering of products and services with a revenue mechanism that is based on selling availability, usage or performance*". This definition was assessed according to the eight criteria for good formal conceptual definitions proposed in [231]. In essence, according to this definition, a PSS is seen as a subset of a corporation's business model, that consists of a particular combination of a value proposition and a revenue mechanism. Besides a new definition, a new PSS representation scheme was presented, that allows to convey the particular defining characteristics of a PSS option: the product and service components that are included in the value proposition, the way those components are integrated and their revenue mechanisms. A PSS typology based on FHM was proposed in Section 5.2, that distinguishes PSS types based on the performance orientation of the dominant revenue mechanism and the level of integration of the value proposition. PSS types can thus be designated as availability-, usage- or performance-based and as segregated, semi-integrated or fully integrated. Within the performance-based type, solution-, effect- and demand-fulfillment oriented subtypes were discerned. The PSS definition, representation scheme and typology, constitute a proposed theoretical basis for PSS research (*contribution* C_2).

As argued in Section 5.5, the main contributions of FHM and the proposed theoretical foundation for the environmental goals of PSS research are twofold:

- The performance-based PSS type, which corresponds to the result–oriented PSS in the traditional PSS typology and which is considered to be the most promising PSS type from an environmental perspective, is better understood by discerning functional results on different levels of abstraction through application of FHM.
- With the new PSS typology, a wide range of PSS options can be identified on the transition path towards a fully-integrated, performance-based PSS type, including options whereby the ownership of the investment good is not transfered towards the provider. This insight can lead to a wider adoption of PSS models in practice, along more gradual transition paths towards a higher level of integration and performance orientation.

In Chapter 6, three complementary methods for PSS ideation were presented (*contribution* C_3). Each of these methods is applicable for supporting the process of generating a varied set of PSS options and chooses one particular theoretical framework: the Product Life Cycle, the Functional Hierarchy Model and the Process Model. According to each method, different types of PSS elements can be identified for inclusion in a PSS option, such as add-on product elements, demand optimization services and process substitutes. The applicability of these methods was demonstrated by presenting PSS options for the cases introduced in Chapter 2.

After setting straight the research questions related to the definition, representation scheme, typology and ideation of PSS, this dissertation moved on to the research questions related to the economic evaluation of PSS options. As clarified in Section 3.4.1, the business potential of a PSS for the provider is determined by four mechanisms:

- cost reduction for existing customers (Mechanism 1)
- value increase for existing customers (Mechanism 2)
- changes to the competitive environment (Mechanism 3)
- a potential expansion of the profitable customer base (Mechanism 4)

Especially Mechanisms 1 and 2 were identified as crucial for the evaluation of the innovation potential of a PSS. In Section 3.4.2, a critical review of eighteen existing theories, methods and tools for the economic evaluation of PSS was presented. The main conclusion from this review was that there is no approach available that focuses on the ex ante evaluation of the innovation potential of a PSS in cost and value while taking into account uncertainties and risks. It was argued that such a method would be a valuable addition to the state-of-the-art. However, in order to achieve practically relevant results, the validity of such an approach should be extensively demonstrated through rigourous case study research.

In Chapter 7, a generic methodology to analyze the innovation potential of a PSS in cost reduction and value increase was presented that meets this research need (*contribution* C_4). This methodology consists of four steps:(1) goal and scope definition, (2) model development, (3) data gathering, output analysis and validation and (4) improvement scenario analysis. Generic structures of input parameters, cost and value aspects and four value quantification strategies were proposed. The impact of uncertainties and risks can be analyzed by combining scenario analysis and Monte Carlo simulation. By linking the PSS options derived in Chapter 6 with specific improvement scenarios in cost and value, the innovation potential of each PSS option can be assessed.

The applicability of this methodology on industrial case studies was extensively demonstrated in Chapter 8 (*contribution* C_5). Four complete cases were described, that were carried out for a manufacturer of traction elevators, a provider of lighting control systems, a provider of fire detection systems and a developer of diamond polishing systems. All steps of the methodology were described and thereby its applicability was demonstrated in various contexts. An additional case for a manufacturer of wind turbine generators was presented to illustrate the analysis of one specific but relevant improvement scenario. A wide variety of methodological aspects were highlighted and practical approaches were demonstrated to tackle them.

Case studies are a widespread research method in the PSS field, which is logical, because they are specifically suitable to study complex phenomena in their context in fields where theory and understanding are not yet well developed. However, many published case studies in the PSS field have drawn criticism for their lack of methodological rigor. In the presented work, these objections are countered by a comprehensive documentation of the research process and design and by taking various measures to enhance the research quality in three dimensions: transferability, truth-value and traceability. Thus, an example is set for future case study research in this field.

9.2 Future research

In this dissertation, a theoretical foundation was proposed for PSS research, and an approach for analyzing the business potential of a PSS for investment goods was presented and validated through case study research. Many opportunities for future research about Product-Service Systems remain, such as the following:

- First of all, the theoretical constructs, methods and tools introduced in this dissertation could be applied for other types of products besides investment goods: e.g. consumer goods, chemicals and medical diagnosis and treatment systems. Especially the following contributions of this research work could be employed: the theoretical PSS constructs (PSS definition, representation scheme and typology), Functional Hierarchy Modeling (FHM) and the quantitative assessment of cost and value. However, a direct translation of the presented theories and methods is not possible, as the following characteristics differentiate investment goods from other types of products:
  - their long lifetime, which makes appropriately dealing with uncertainties and risks more important
  - the fact that their value for the customer is often quantifiable as their economic impact on the customer's operations. For consumer goods, intangible value aspects are expected to be more important.

  - the fact that often a significant amount of consumables, spare parts and energy are consumed during their lifetime, thereby increasing the likelihood that there is an innovation potential related to these aspects.

- The presented work focuses on the economic quantification of the PSS innovation potential, while a quantification of the ecological impact was not pursued. We see an opportunity for assessing the ecological innovation potential of a PSS, whereby a significant overlap is expected with the cost evaluation of Chapters 7 and 8. The inclusion of uncertainties and risks in a Life Cycle Assessment is a topic that is not sufficiently covered in the current literature. Especially performance-based PSS types should be investigated, whereby a comparison could be made between solution, effect and demand fulfillment oriented PSSs. Thus, the hypothesis formulated in Section 5.5, that the potential for environmental impact reduction is higher for PSS types related to a higher level of abstraction of the FHM, could be substantiated.

- The proposed methodology is geared towards an ex ante evaluation of the cost and value potential of a PSS. However, other mechanisms that determine the business potential of a PSS are the expansion of the customer base and changes to the competitive environment. Future research could address these particular mechanisms, by incorporating techniques from pricing research, based on the extraction of customer information that allows to estimate actual WTP. In addition, the competitive dynamics related to the introduction of a PSS are not well understood in the current literature, and an approach that allows to simulate and quantify the potential growth of the customer base would be a valuable addition to the state of the art. Such an approach could be based on game theory or agent based modeling.

- A factor which was not included in the presented case studies is how to deal with the complexity of a network of subcontractors. Besides the revenue mechanism that describes how the customer pays for the value proposition to the provider, *internal* revenue mechanisms can be identified that describe how subcontractors are paid for their contribution to the delivery of a PSS. An analysis of the business potential of various PSS options that are distinguished based on these internal revenue mechanisms could provide additional insights.

- During discussions with representatives of companies interested in implementing a PSS, one specific issue emerged as an important risk of such a move, namely how the behavior of users or other stakeholders would change under a PSS model. If systems are sold according to a usage, availability- or performance-based revenue mechanism and especially in cases where ownership is not transfered towards the user, potential changes in how careful and correct these systems are used could be highly influential on the profitability of a PSS. Approaches for predicting and mitigating such behavorial changes could be addressed by future research.

Appendix A

FHM examples

This appendix to Chapter 4 contains more examples of teleological chains and Functional Hierarchy Models for some of the cases introduced in Chapter 2. Figures A.1, A.2 and A.3 present the teleological chains of a traction elevator (case α), a lighting system (case β) and a fire detection system (case γ). Figures A.4 and A.5 present the FHMs of a lighting system (case β) and a fire detection system (case γ).

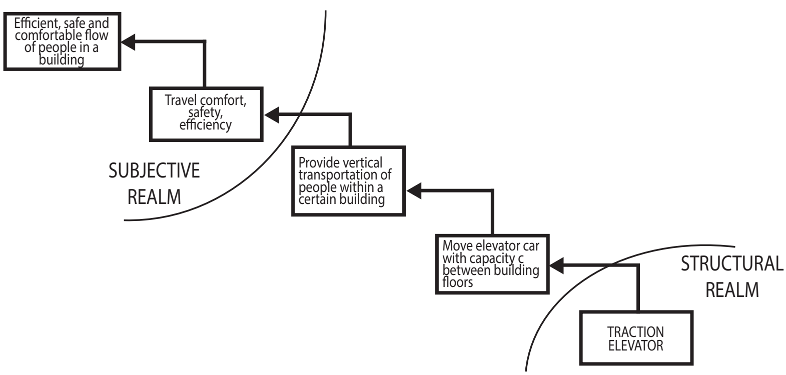

Figure A.1: Teleological chain of a traction elevator (case α).

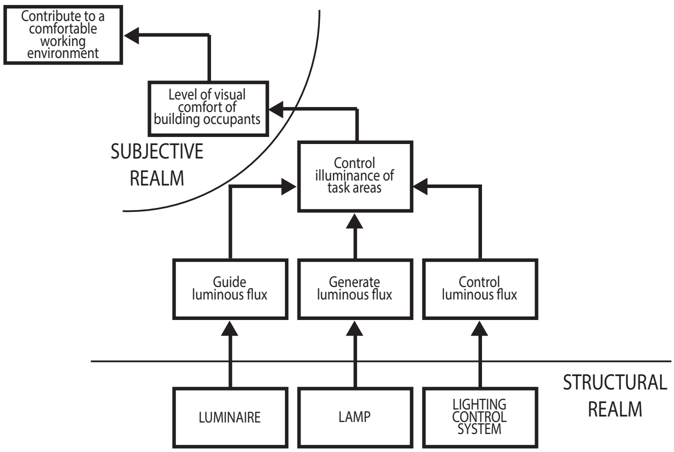

Figure A.2: Teleological chain of a lighting system (case β).

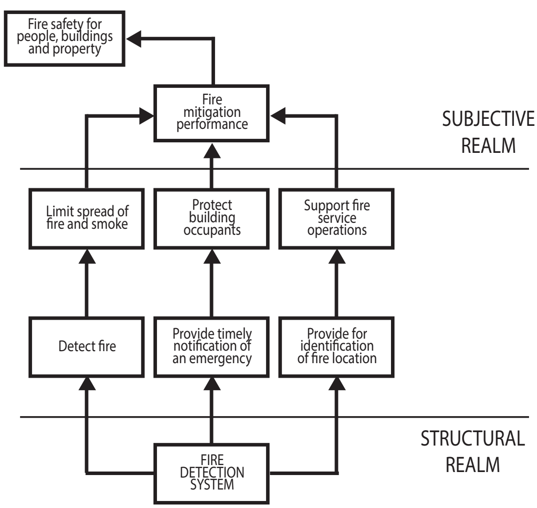

Figure A.3: Teleological chain of a fire detection system (case γ).

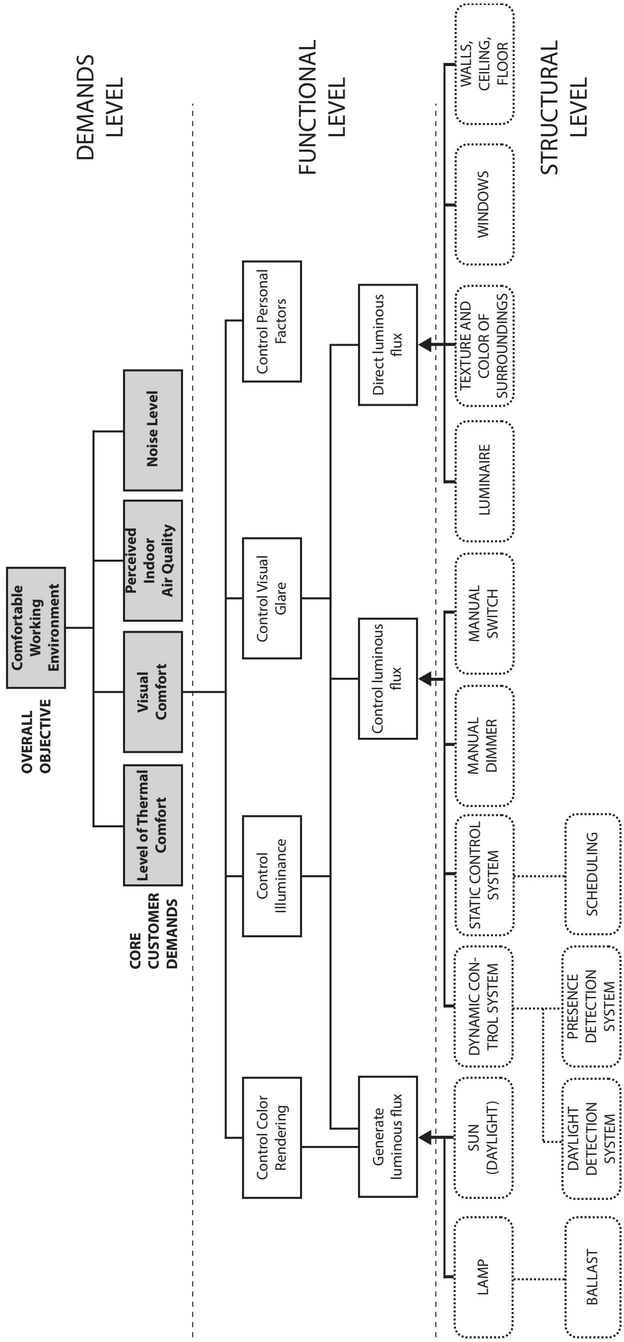

Figure A.4: FHM of a lighting system (case β).

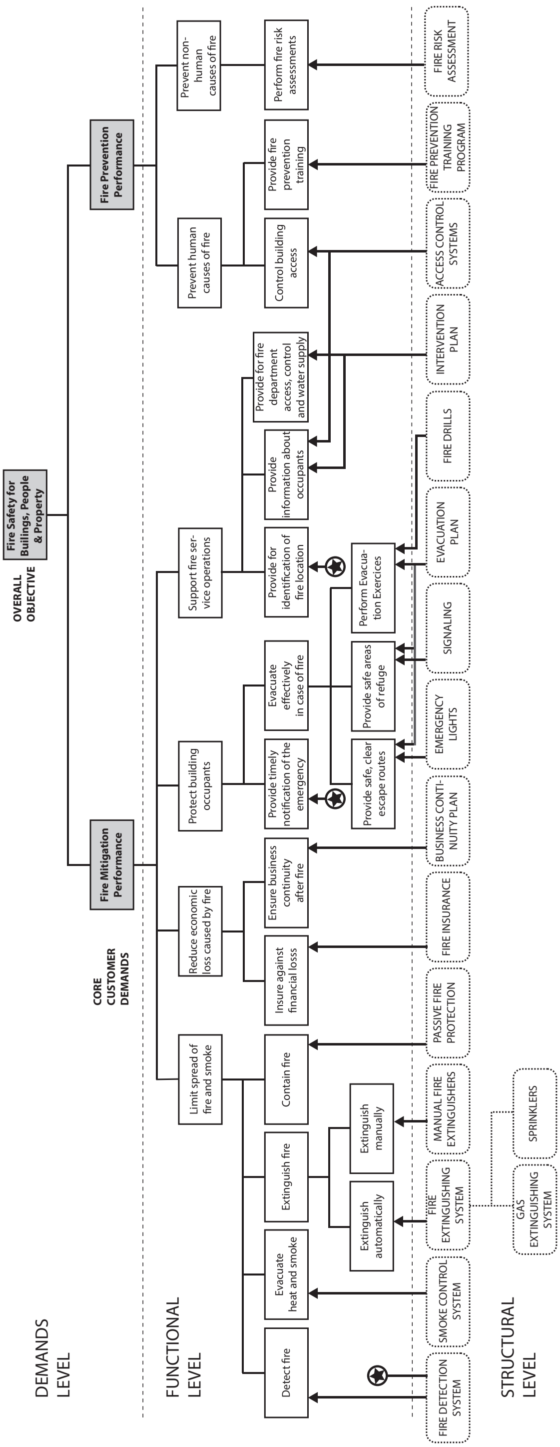

Figure A.5: FHM of a fire detection system (case γ).

Appendix B

Additional information for Case α

This appendix to Section 8.1 of Chapter 8 contains more information on Case α. In Section B.1, the system boundaries are presented. Section B.2 describes the approach for calculating the thermal losses in the elevator shaft. Section B.3 presents the main information sources, the way the energy measurements were performed and the main statistical distributions chosen for modeling the input parameters.

B.1 Step 1: Goal and scope definition

The system boundaries chosen for case α are provided in Table B.1.

Table B.1: System boundaries for Case α.

Time horizon	20 years
Geographical location	Within 200 km from the headquarters of Company α
Technical system	• Only one specific type of gearless, machine roomless traction elevator is included in the study • The elevator shaft and ventilation grid are not considered to be part of the system • The number of floors in a building are between 2 and 9 (representative for the Belgian market)

B.2 Step 2: Model development

The thermal loss through the elevator shaft was calculated according to the following approach, which is only valid for buildings that are *not* energy class A or B according to the Energy Performance of Buildings Directive 2010/31/EU (EPBD) [82, 140]:

$$Q = m \times c \times \Delta T \tag{B.1}$$

In Equation B.1 Q is the thermal loss in Watt, m the mass flow of air leaving the building in kg per second, c the average specific heat capacity of air (1,005 J/kgK) and ΔT the difference in temperature between the outside air and the interior of the elevator shaft. The mass flow of air leaving the building is determined as follows:

$$m = A_{out} \times v \times \rho \tag{B.2}$$

In Equation B.2 A_{out} is the the surface area of the ventilation grid opening, v the air velocity in meters per second and ρ the air density in kg per m³. The air velocity can be determined by applying the following equation [180, 140]:

$$v = \sqrt{\frac{g \cdot h \cdot \Delta T / T_{int}}{1 + A_{out}^2 / A_{in}^2}} \tag{B.3}$$

with T_{int} the interior temperature in the building, A_{in} the surface area of all openings around the elevator doors on each floor[1], g the gravititational acceleration and h the height of the shaft.

B.3 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table B.2, the main information sources for case α are listed.

Some results of the energy measurements (cfr. Table B.2) are presented in Figure B.1. In this figure, for one particular combination of elevator acceleration

[1]This opening is prescribed according to a European standard as a percentage of the total surface area of the door.

Table B.2: Main information sources for Case α.

Input parameter	**Information source**	**Type of information source**
Number of travel cycles	Recorded number of travel cycles from a large hospital with 58 elevators.	Historical data
Energy savings potential for elevator renovation	Recorded data and technical reports from a large hospital.	Historical data
Active and passive energy consumption	Power and time measurements were performed at one of Company α's customers. These measurement were performed according to VDI 4707-01 [227] for eight combinations of velocity, acceleration and loading and for different subsystems	Measurements
Failure rates and failure impact (materials, labor,. . .) for 15 failure modes	Estimated independently by R&D expert and by two service technicians as well as a service coordinator.	Internal experts
Parameters for determining the thermal losses	Based on assumptions mentioned in a research report prepared for the company AFC by the Centre de Recherche Public Henri Tudor [140].	External experts, historical data
Cleaning time per elevator per day	Estimated by supervisor of a cleaning team in a large hospital.	External experts

and velocity, the recorded power is shown over the length of the reference cycle (which is in this case about 80 seconds and defined according to VDI 4707-01 [227]). The surface under the curves represents the energy consumption. These measurements were performed for four different loadings (0, 27, 53 and 81% of the rated capacity of the elevator). On the left side of Figure B.1, the travel downwards is visible, on the right side the travel upwards. At the beginning and at the end of the travelling mode, the 'spikes' represent the opening and closing of the doors. Due to the counterweight, the elevator consumes more energy when traveling at 0% loading then at 50% loading. Apart from the active energy consumption, the standby energy consumption was determined for the different subsystems by measuring power while switching them off selectively.

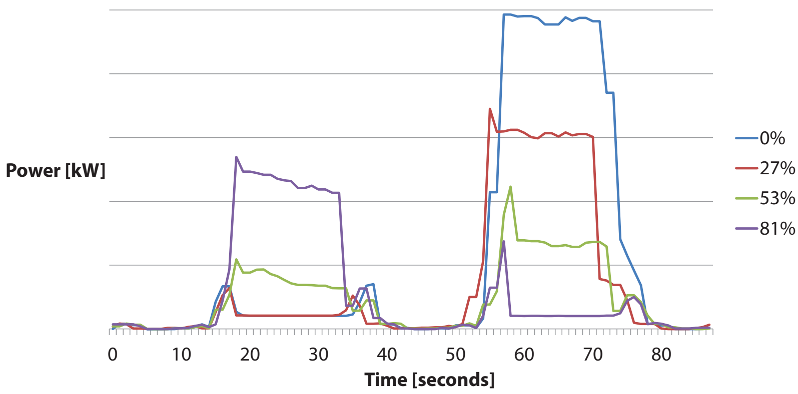

Figure B.1: Results of the power and time measurements for Case α, for four different loadings (0, 27, 53 and 81% of the elevator's rated capacity). The scale of the Y axis is not included for confidentiality reasons.

Uncertainties and risks

The most important and noteworthy choices for statistical distributions that represent the uncertainties in the input parameters are explained in Table B.3.

Table B.3: Main statistical distributions used to represent the uncertainty in certain input parameters for Case α

Input Parameters	**Types of distribution**	**Explanation**
Number of travel cycles	Bounded normal (within each scenario)	For elevators within the same usage class, the number of travel cycles per year is expected to be normally distributed, which is confirmed by distribution fitting on the historical data according to maximum likelihood estimation.
Number of floors	Discrete distribution	In the simulation model, a building has between 2 to 9 floors, with equal probabilities (i.e. 12,5%).
Failure rate	Discrete distribution or calculated through exponential distribution.	For some failure modes, the number of failures in 20 years is modeled as a discrete distribution whereby experts estimate the probability that 0, 1, 2 or 3 failures occur in 20 years. For other failure modes, the consecutive times to failure are calculated by using an exponential distribution (assuming a time independent failure rate).
Cable lifetime	Distribution determined by the number of travel cycles and conditional logic	Cables are to be replaced after 1.2 million travel cycles or after 8 years of operation. When one of both conditions is reached, the replacement is performed.
Distance	Combination of discrete and uniform distributions	Distance is partitioned into classes (e.g. 0-20, 21-50, 51-100) each of which are assigned a probability with a discrete distribution and within each class an exact distance is sampled from a uniform distribution.
Repair, coordination and diagnosis times	PERT distributions (Beta)	The distributions for these parameters are estimated by experts as a minimum, most likely and maximum value. For almost half of the failure modes, a conditional logic was programmed into the model, that allowed to represent the need and impact of diagnosis, re-diagnosis and repairs.

Appendix C

Additional information for Case β

This appendix to Section 8.2 of Chapter 8 contains more information on Case β. In Section C.1, the system boundaries are presented. Section C.2 describes the approach for calculating the energy savings realized by an LCS. Section C.3 presents the main information sources, clarifies the choices for the statistical distributions and presents the results of the cost and value analysis for the old offices subsegment.

C.1 Step 1: Goal and scope definition

The system boundaries chosen for case β are provided in Table C.1.

C.2 Step 2: Model development

In this section, an example is presented of how five point estimates were derived for modeling the dependency of activity durations on the quality parameters introduced in the model (cfr. Table C.2). Subsequently, the approach to calculate the *energy savings* due to implementation of an LCS is described and the main differences with the analysis method for the old offices are presented.

Table C.1: System boundaries for Case β.

Time horizon	20 years
Geographical location	Within 400 km from the headquarters of Company β
Technical system	• An LCS consists of daylight sensors, movement sensors, control units, cables and input-output modules. • Only for old offices, lamps, luminaires, ballasts, wiring and manual lighting control are within the system boundaries. • Roof openings (e.g. rooflights, light domes) are not taken into account. • Only linear fluorescent lamps are considered. • Only DALI connections are taken into account. • We assume that both for the old and the recent offices, the illuminance of all task areas is according to the relevant standards (e.g. EN 12464-1 [36]) and thereby we disregard environments were the current lighting system is not appropriately engineered. • For the old offices, the analysis was made for only five combinations of lamp, luminaire and ballast (LLB). For the recent offices, only one LLB combination was included in the analysis. Their choice is explained in Section 8.2.3. • For the recent offices subsegment, only landscape offices are taken into account, and not cellular offices. • Emergency lighting is not included within the system boundaries. • Subsidy mechanisms are not taken into account.

Table C.2: Example showing three activities, the quality parameter on which their duration depends (if any) and the activity drivers that determine how many activities are performed per project.

Activity	**Quality parameter**	**Duration [minutes]** very bad	bad	normal	good	very good	**Activity driver**
Electrical troubleshooting	installation work	2400	1440	480	360	240	per project
Configuring calendars of the LCS	specifications	15	10	5	4	3	per calendar
Caibration of daylight sensors (DLSs)	none	3	3	3	3	3	per DLS

Calculation of energy savings for recent offices The approach to calculate the energy savings incurred by an LCS consists of the following steps:

1. We start from the characteristics of a building, that are represented by some of the customer parameters of Figure 8.10. These characteristics are the relevant surface area in m^2, the dimensions of the office rooms in the building, the width, heighth and length of the offices, the reflection coefficients of the walls and the surface area of the windows.

2. We presume that the lighting system consists of a certain combination of luminaires, lamps and ballasts (LLB). The LLB combination considered consists of luminaire type A1.3 (a ceiling-type, refractive luminaire, cfr. Table 66 of [222]), 2 LFL T8 36W lamps and an electronic dimmable ballast type A1. The reasons why this particular combination is selected are the following:

   - It is included in a VITO report on lighting systems in office buildings (2007) [222] as one of the most prevalent lighting systems in Belgian offices.
   - If compared to the other LLB combinations present in Belgian offices, it can be considered as best available technology in 2007 due to its energy efficiency, expressed by its New Power Density[1] and its life cycle costs [223].
   - It is the only best available technology LLB combination specified in [222] with a ballast type appropriate for directly implementing an LCS (i.e. an electronic dimmable ballast).

3. With this particular LLB combination, the lighting system of the building is designed by application of the *lumen method*, a simplified and commonly used method to calculate how many luminaires and lamps are required to ensure that a building is lighted according to standard specifications [191]. The basic equation used in the lumen method is as follows:

$$\Phi_{inst} = \frac{E_{main} \cdot A}{MF \cdot UF} \tag{C.1}$$

   Equation C.1 represents the luminous flux Φ_{inst} (in lumens) that needs to be provided to achieve a *maintained illuminance* E_{main} ($E_{main} = 500$ lx according to the European standard 'EN12464' [36]) of a task area A assuming a depreciation of the lighting system over its maintenance cycle

[1] Net Power Density is a measure of the efficiency to illuminate a specific task area [81].

(represented by a *maintenance factor* MF) and a "lighting efficiency" represented by a *utilization factor* UF (determined by the European standard 'EN13032' [34]). Through this approach, the total number of luminaires, lamps and ballasts that are installed in the building are determined.

4. Now that the lighting system is designed, the potential savings of the LCS in kWh can be determined based on European standard 'EN15193' [35], with main Equation C.2.

$$W = \frac{\sum P_n \cdot F_c \cdot (t_D \cdot F_O \cdot F_D + t_N \cdot F_o)}{1000} + W_{P,t} \tag{C.2}$$

   Equation C.2 determines the total energy consumption of the lighting system as the sum of the active energy consumption (the left term) and the parasitic energy consumption $W_{P,t}$[2]. The left term of Equation C.2 represents the energy consumed during the actual use of the installed power of the lighting system P_n (derived from the installed lumens Φ_{inst}) through factors F_c, F_O and F_D, which represent the savings from *constant illuminance control*, *occupancy control* and *daylight control* during daylight time t_D and non-daylight time t_N respectively. The parameters F_c, F_O and F_D are expressed as a fraction and reflect the efficiency of the LCS.

5. The parametric relations to derive estimates for the factors F_c, F_O and F_D are also based on parametric relations presented in EN15193 [35]. Various customer specific parameters are inputs to these formulas (e.g. the total surface area of windows, lamp's maintenance factors, ...). The detailed formulas to determine these factors and estimates can be found in EN15193 [35] and [223].

6. The energy savings are calculated by subtracting the energy consumption determined according to Equation C.2 from the energy consumption before implementation of the LCS. By multiplying these savings with an electricity price, the actual cost savings are determined.

7. To have a clearer view on the contribution of the various lighting control strategies, the following scenario's were defined:

   - *Lighting control strategy 1*: application of time control and constant illuminance control
   - *Lighting control strategy 2*: application of constant illuminance control and occupancy control

[2] In EN15193 [35], $W_{P,t}$ is determined as the sum of the parasitic energy consumption of the emergency lighting and of the LCS. Since we do not consider the emergency lighting to be a part of the lighting system, we disregard the first term.

- *Lighting control strategy 3*: application of time control, constant illuminance control and daylight control.
- *Lighting control strategy 4*: application of constant illuminance control, daylight control and occupancy control.

For each scenario, the potential savings were determined.

Calculation of energy savings for old offices The main differences between the old offices analysis and the recent offices analysis are the following (for more details, cfr. [223]):

- In the analysis of old offices, different LLB combinations are considered for the current lighting system. For the old offices subsegment, the LLB combinations are chosen with the worst Net Power Density and LCC performance, i.e. the most costly and energy inefficient systems that are present on the Belgian office market according to [222]. In total 31 LLB combinations were compared, of which 5 LLB combinations were chosen as a base case scenario. As these LLB combinations will have the largest savings potential, they are identified as the most promising for the implementation of a PSS.

- The old offices subsegment includes the complete renovation of the old lighting system by a new lighting system before implementation of the LCS. The new lighting system is defined by choosing the best performing LLB combination with regards to Net Power Density/LCC performance. This corresponds to the LLB combination of the recent offices subsegment. All costs of implementing the new lighting system are taken into account as indicated in the design and production phase of Figure 8.9.

- Not only landscape offices but also celullar offices are taken into account.

- The savings are also calculated for different scenarios: the scenario whereby only the lighting system is replaced and the four scenarios for lighting control defined in Section 8.2.1.

- Besides energy costs, maintenance and lamp replacements costs are also taken into account.

C.3 Step 3: Data gathering, output analysis and model validation

This section describes the main information sources for case β (in Table C.3), some notable choices made for the distributions (in Table C.4). Subsequently, the output analysis (cost and value) for the old offices segment is presented.

Table C.3: Main information sources for Case β.

Input parameter	**Information source**	**Type of information source**
Number of control units, sensors, etc	Recorded data of past projects	Historical data
Specifications of the luminaire-lamp-ballast combinations	Data published in reference [222].	Historical data
Number of activities and resources per activity for sales support, pre-configuration, configuration, etc.	Estimated by business unit director and project manager	Internal experts
Number of activities and resources per activity for wiring and installation	Estimated by technicians of installation company	External experts
Various parameters to determine the energy consumption for the four lighting control strategies	Values provided in EN15193 [35], for more details see Table 4.5 on pages 83–84 of [223]	Literature
Office dimensions	Values provided in EN15193 [35] and in the VITO report [222].	Literature

Table C.4: Main statistical distributions used to represent the uncertainty in certain input parameters for Case β.

Input Parameters	**Types of distribution**	**Explanation**
Quality categories	Discrete distribution	Since there were no data or expert knowledge available to estimate the probability that the quality of plans, specifications and installation work is within a certain category, each category (e.g. good/average/bad) was modeled as equally probable.
Electricity price (€/kWh)	Uniform distribution	It was decided in coordination with the central project team not to model the electricity price as a time series (i.e. representing a certain price evolution) but rather to model an average electricity price over the total study period, as a uniform distribution.
Distance	Combination of discrete and uniform distributions	Distance is partitioned into classes (0-50, 51-100, 101-200, 201-400) each of which are assigned a probability with a discrete distribution (20%, 40%, 20%, 20%). Within each class, the distance is assumed uniformly distributed.
Duration of the activities in the design and production phase	PERT and uniform distributions	The distributions for these parameters are estimated by experts as a minimum, most likely and maximum value.
Office dimensions	Discrete distributions	Office dimensions such as width, heighth, surface of windows were modelled as discrete distributions.

Value analysis for recent offices In Figures C.1 and C.2, electricity prices are presented for two customer categories as defined by Eurostat (medium-sized industrial and household customers), for selected (mainly Western-)European countries. From these figures, it is apparent that there is a significant geographical variability of the electricity price.

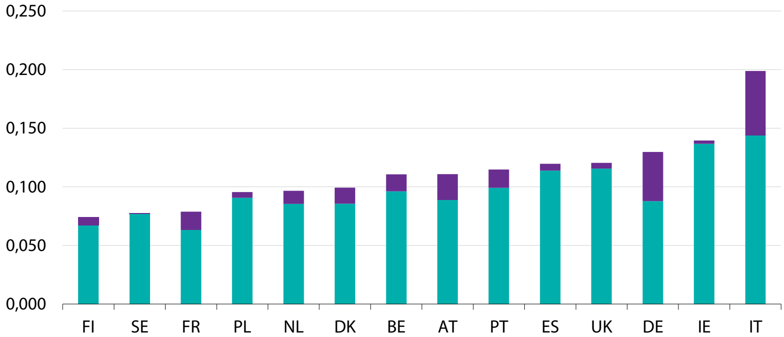

Figure C.1: Average electricity price (2012) in $^{€}/_{kWh}$ for medium-size industrial customers in selected European countries, decomposed into basic price (blue) and non-recoverable taxes and levies (purple). Country codes are according to ISO 3166–1 (source: Eurostat).

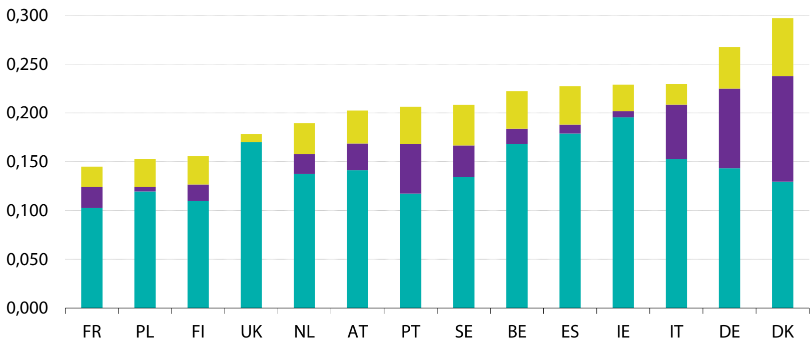

Figure C.2: Average electricity price (2012) in $^{€}/_{kWh}$ for households in selected European countries, decomposed into basic price (blue) VAT (yellow) and other taxes (purple). Country codes are according to ISO 3166–1 (source: Eurostat).

Cost analysis for old offices For the cost analysis for old offices, only the main results are presented here (the underlying output analyses are presented in [223]):

- In Figure C.3 the decomposition of the average initial investment to replace an outdated lighting system and to subsequently implement an LCS in a landscape office is presented. Figure C.3 demonstrates that the LCS does not account for the largest part of the initial investment: the most significant cost categories are related to the luminaires, the installation of the luminaires and the labor-related costs for cabling. Naturally, if Company β would implement option $PSS_{\beta 4}$ of Table 6.3 as a hybrid offering with external partners, the most important partners to select are the luminaire manufacturer and the electrical installation company.

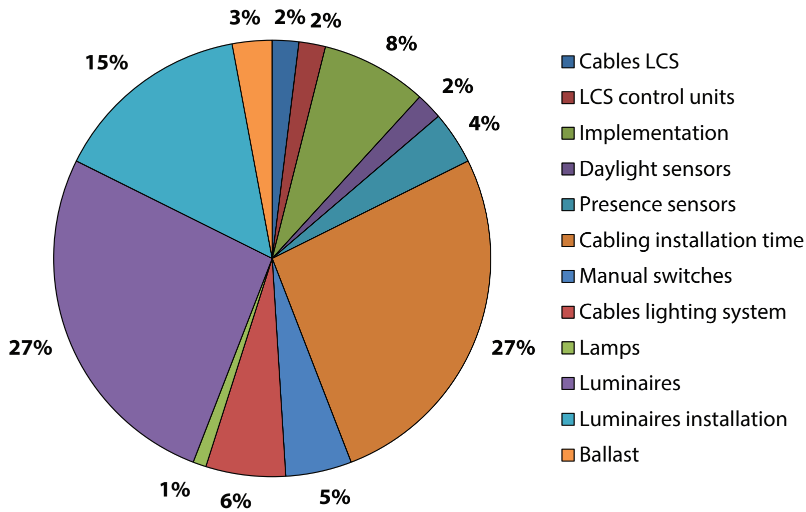

Figure C.3: Pie chart of the average initial investment in the renovation of an outdated lighting system in a landscape office and the implementation of an LCS (Strategy 4), decomposed into categories (adapted from [223]).

- If Company β would assume responsibility for managing the lighting and lighting control system of its customers over a period of 20 years, including the payment of energy costs, the total Life Cycle Cost for various lighting control strategies and office types is presented in Table C.5. Cellullar offices require a significantly larger initial investment than landscape offices and a more advanced lighting control strategy requires a larger initial investment but achieves superior energy savings [3].

Table C.5: Decomposition of the total LCC of a lighting system for cellullar offices (CO) and landscape offices (LO) for the four lighting control strategies of Section 8.2.3 into initial investment, energy cost and lamp replacement costs (adapted from [223]).

	Initial investment	Energy cost	Lamp replacements
CO, Strategy 1	69%	30%	1%
CO, Strategy 2	75%	24%	1%
CO, Strategy 3	77%	21%	1%
CO, Strategy 4	82%	17%	1%
LO, Strategy 1	58%	41%	1%
LO, Strategy 2	60%	38%	1%
LO, Strategy 3	61%	38%	1%
LO, Strategy 4	63%	35%	1%

Value analysis for old offices The main results obtained from the value analysis for old offices are the following:

- In Table C.6 the profitability indicators are presented for the implementation of a new lighting system in an old office, with or without LCS according to Strategy 4. The conclusions of the value analysis for old offices are the following:
  - The discounted payback periods (DPBs) are significantly longer than those for the new offices segment, that were restricted to the implementation of lighting control. The combination with an LCS has a positive effect on the NPV and DPB.
  - For cellullar offices, the large initial investment that is required in the lighting system impedes the profitability of the implementation. On average, the NPV over 20 years is negative for old offices.

[3] The attentive reader might notice an apparent contradiction between Table C.5 and Figure 8.14: the ranking of lighting control strategies 2 and 3 is reversed. The reason is that in the simulation for old offices, the abscence factor F_A is chosen to be in the interval [0, 20%], while for the recent offices segment the interval [10%, 30%] was chosen, which results in higher savings due to occupancy control. The second choice is deemed preferable, as occupancy control should only be applied in offices where there is a minimal abscence. In the analysis of the old offices subsegment however, consistency with [223] is preferred.

Table C.6: Value analysis of an LCS in an old office, for lighting control strategy 4, with selected performance indicators: Net Present Value (NPV), Discounted Payback Period (DPB), Payback Period (PB), Initial investment (I_0) and Profitability Index (PI).

		Landscape Offices		Cellullar Offices	
		Manual	Strategy 4	Manual	Strategy 4
I_0 [€/m^2]		31,7	40,8	49,1	69,3
NPV [€/m^2]	10%	-8,7	-5,3	-25,0	-29,0
	average	7,0	12,2	-8,2	-9,8
	90%	24,3	32,7	10,3	11,8
DPB [years]	10%	6,6	6,7	12,8	13,7
	average	17,2	15,2	26,0	26,1
	90%	/	/	/	/
PB [years]	average	8,0	7,2	12,2	11,0
$PI = {}^{NPV}/_{I_0}$ [%]	average	22%	30%	-17%	-14%

– The critical factors that determine the additional value of the implementation of a new lighting and lighting control system are the following [223]: the electricity price, the room index and the type of luminaire-lamp-ballast combination that is being replaced. For old offices, the relation of the NPV/DPB with the room index is reversed in comparison to the analysis for new offices. Now, a higher room index results in a lower initial investment in the lighting system. The opposite effects of the room index on the daylight control gains are surpassed.

Appendix D

Additional information for Case γ

This appendix to Section 8.3 of Chapter 8 contains more information on Case γ. In Section D.1, the system boundaries are presented. Section D.2 presents the main information sources, the main statistical distributions chosen for modeling the input parameters and the value analysis.

D.1 Step 1: Goal and scope definition

The system boundaries chosen for case γ are provided in Table D.1.

Table D.1: System boundaries for Case γ.

Time horizon	20 years
Geographical location	Within 100 km from the headquarters of Company γ
Technical system	• An FDS consists of detectors, push buttons, batteries, I/O modules, sirens, control panels, wiring • Only spot or single point detectors included in the study (e.g. no ‘beam detectors’) • Other fire safety systems (e.g. sprinklers) are not within the system boundaries • The system is considered to be designed and maintained according to the applicable fire safety standards (NBN S21-100).

D.2 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table D.2, the main information sources for Case γ are listed.

Table D.2: Main information sources for Case γ

Input parameter	**Information source**	**Type of information source**
Area per node (detector, siren, . . .)	Recorded data of past projects	Historical data
Number of node failures	Recorded data of existing systems for which a maintenance contract exists	Historical data
Number of activities and resources per activity (e.g. for installation, commissioning, revision, maintenance)	Estimated by operations manager, service manager and installation project leader.	Internal experts
Fire insurance rates and discounts for customers in case an FDS is installed	Estimates provided per €1000 of insured value by two experts from different insurance companies	External experts

Uncertainties and risks

The most important and noteworthy choices for statistical distributions that represent the uncertainties in the input parameters are explained in Table D.3.

Table D.3: Main statistical distributions used to represent the uncertainty in certain input parameters for Case γ.

Input Parameters	**Types of distribution**	**Explanation**
Number of failures	Poisson distribution	The number of detector failures in a certain year is determined as Poisson($\lambda \cdot N$) with λ the estimated failure probability per node and N the number of nodes. Thus, the failure probability is assumed to be time-independent.
Distance	Combination of discrete and uniform distributions	Distance is partitioned into classes (0-50, 51-100, 101-200, 201-400) each of which are assigned a probability with a discrete distribution (20%, 40%, 20%, 20%). Within each class, the distance is assumed uniformly distributed.
Number of detectors, sirens, push buttons, ...	Combination of discrete and uniform distributions	Based on historical data, these parameters were modeled in a similar way as the parameter *distance*. For example, to determine the number of input-output modules in a building, the surface area could belong to three classes: none, between 80 and 120 m² per module and between 1000 and 1500 m² per module.
Duration of all activities	PERT and uniform distributions	The distributions for these parameters are estimated by experts as a minimum, most likely and maximum value.

Value analysis

In the value analysis for FDS, the performance indicators marked in bold in Table 8.11 were subjected to a further investigation.

To obtain information for estimating the performance indicator '***effect on fire insurance tariffs***', two fire insurance specialists were interviewed. The following insights were derived:

- The orders of magnitude of an office building owner's expenses for fire insurance and for an operational FDS are the following: the yearly expense for insuring a typical office building of $10.000m^2$ against fire risks would be about 10–15k€, depending on many factors such as the real estate value, the value of the building contents and the commercial discounts given at that particular moment by the fire insurer. The equivalent annual expense for an FDS (including initial investments and in-service costs) would also be of an order of magnitude 10k€.
- Fire insurance focuses solely on the value of building and property, while an FDS is mainly considered to be a means to notify (and thereby protect)

building occupants. Therefore, the technical discounts given on the insurance premium for customers with an FDS is very limited. One informant estimated the technical discount to be only about 0,5% (i.e. for our example an annual discount of only 50-75 €).

- Fire extinguishing systems have a more profound impact on fire insurance tariffs than FDS's, as discounts of up to 60–70% can be given on fire insurance premiums if a particular fire extinguishing system is implemented.

- Thus, the potential of combining an FDS and fire insurance were seen as limited due to their limited mutual influence. Another hurdle for such a combination is the legislation regarding product tying.

The value component '***impact on fire safety risks***', which consists of the performance indicators '*effect on probability of (non-)fatal casualties in case of fire*' and '*effect on property damage impact of fire*' is key to the value of an FDS. However, deriving reliable estimates for these indicators is far from evident. Overall, there is a limited availability of detailed fire statistics worldwide. On the Belgian and European level, no statistics were found. A report of the US National Fire Protection Association investigates the occurences of fires in offices in the US during the period 2007–2011 [31]. According to this report, if a fire occurs, the probability of a fatal and non-fatal casualty is 0,12% and 1,3% respectively, while the average property damage per fire is 33.532 US$. The leading causes of fires in office buildings are cooking equipment (29% of fires), electrical distribution and lighting equipment (12%), heating equipment (11%) and arson (10%) [31]. The effect of an FDS on the impact of fires is not specified in [31].

In a report of the UK Department for Communities and Local Government, the effect of fire detection systems on the probability of fatal and non-fatal casualties in non-residential buildings for the period 2006 – 2012 are presented (cfr. Table 3.1 on page 48 of [45]). Besides office buildings, this category includes other buildings such as hotels, schools and hospitals. If there is a fire, the probability of a fatal casualty is 0,1236% for a building without FDS and 0,0871% for a building with FDS. For non-fatal casualties, the probability is actually higher if there is an FDS: i.e. 6,34% versus 4,49%. However, concluding that with an FDS the probability of a non-fatal casualty is larger is not advised, as buildings equipped with an FDS are most likely those that have a larger risk of casualties in case of fire (and for which an FDS is prescribed according to building codes). If the FDS functions correctly, the probability of a non-fatal casualty is 5,89%, while if an FDS is present but does not function correctly, this probability is 7,65% [45].

The probability that a fire occurs is expressed by the *ignition frequency* per year per m^2 of office area. Specific ignition frequencies for office buildings are only provided in a few sources. In [166], the ignition frequency of office buildings is estimated to be $2,1 \cdot 10^{-6}$, based on data for Finland in the period 1996–1999. In that report, in comparison to other building types, the ignition frequency for office buildings is lower. In [178], for Swedish offices in the period 2000–2002, an ignition frequency of $4,0 \cdot 10^{-6}$ was derived.

While the presented statistics allow to get an impression of the order of magnitude of the performance indicators related to an FDS's impact on the fire safety risks of a building, they are certainly not representative, detailed and reliable enough to be able to estimate how much value could be added by adapting certain design parameters of the FDS. Therefore, the quantification of these indicators was not pursued any further.

Appendix E

Additional information for Case δ

This appendix to Section 8.4 of Chapter 8 contains more information on Case δ. In Section E.1, the system boundaries are presented. Section E.2 presents the main information sources, the main statistical distributions chosen for modeling the input parameters and certain aspects of the value analysis of polishing with an automatic DPS.

E.1 Step 1: Goal and scope definition

The system boundaries chosen for case δ are provided in Table E.1.

E.2 Step 3: Data gathering, output analysis and model validation

Sources of information

In Table E.2, the main information sources for case δ are listed.

Table E.1: System boundaries for Case δ.

Time horizon	The lifetime of the automatic diamond polishing system (DPS) is presumed to be in between 10–15 years. The study period for the LCC analysis is 15 years.
Geographical location	The assumption is made that the automatic DPS is located in Belgium.
Technical system	• Only ‘brilliant cut’ is taken into account, which is the most common diamond cut. • Rough diamond stone types are restricted to the most common types. Rough diamonds can be classified according to their shape into categories such as *sawable one*, *sawable two*, *makeable one*, *flats*, … The main difference between these categories is their maximum possible recovery weight (ratio of final over initial weight, also known as yield). To control the complexity of the analysis, only recovery weights between 40 and 55% are taken into account. • Only *automated* application of the GIP technology is taken into account. In principle, GIP can be applied as well in a manual process, but this option was not analyzed. • The costs related to the building, administration, security and insurances were not included in the analysis of the cost of the automatic DPS, but were added as an overhead to the labor cost.

Table E.2: Main information sources for Case δ

Input parameter	**Information source**	**Type of information source**
Price of finished stone per carat	Price catalogue of online retailer with 16.480 diamonds in segments A, B, C and D, in combination with commercially available pricelist (Rapaport)	Historical data
Price of rough diamonds	Commercially available pricelist (Adtec)	Historical data
Activity and technical parameters of GIP polishing	Estimates provided by three Company δ representatives	Internal experts
Transport costs to China, India	Approximate rates supplied by specialized diamond transportation companies, expressed in US\$ per 1000 US\$ of transported value	External experts
Activity and technical parameters of all current process steps in the cutting and polishing stage	Estimates provided by representatives of three diamond processing companies	External experts
Market values for the cost of polishing in India and China for the different segments	Estimates provided by representatives of four diamond processing companies	External experts

Uncertainties and risks

The most important and noteworthy choices for statistical distributions that represent the uncertainties in the input parameters are explained in Table E.3.

Table E.3: Main statistical distributions used to represent the uncertainty in certain input parameters for Case δ.

Input Parameters	Types of distribution	Explanation
Price per carat of finished stone	Dagum distribution	Based on the sample of 16.480 stones, a distribution of the price per carat was determined by fitting it on the available data. The Dagum distribution was the best fit according to maximum likelihood estimation [229]. This is remarkable, given the fact that the Dagum distribution was proposed as a model of personal income distribution [46], cfr. Figure E.1.
Ratio of finished to rough price per carat	Uniform distribution	Pricelists for rough diamonds were analyzed and compared with pricelists for finished diamonds. Within three carat categories (e.g. 0,50-0,69ct), for 12 of the most common combinations of clarity and color, both prices were determined. Then, the ratio of finished to rough price was calculated. Thus the total range of this ratio was determined and it was modeled as a uniformly distributed input parameter to the model.
Cost and value impact of 'tension stones'	Combination of discrete and uniform distributions	In the scenario where tension stones are taken into account, tension stones are assigned to one of four 'tension categories' according to a discrete distribution. In each category, the extra processing time is determined by a uniform distribution and the probability of damage and impact of damage as deterministic values. Estimates for these parameters were provided by an industry expert.
Processing times	PERT distributions	The distributions for the processing times of the activities planning, sawing, etc. were estimated by external experts as an three point estimate, minimum, most likely and maximum value.
Processing times of DPS	PERT distributions	In the variable process parameters scenario, the time to polish one diamond with the DPS is determined by a base time per stone and a surcharge per carat removed, both modeled as PERT distributions.
Technical DPS parameters	PERT distributions	The distributions for technical parameters of the DPS (e.g. tool life, cost of polishing disk) were estimated by experts as a pessimistic, most likely and optimistic value. For certain consumables, the useful life was expressed as the number of stones that could be polished, while for others it was expressed as the number of carats that could be removed. This was determined based on the insights of the internal experts.

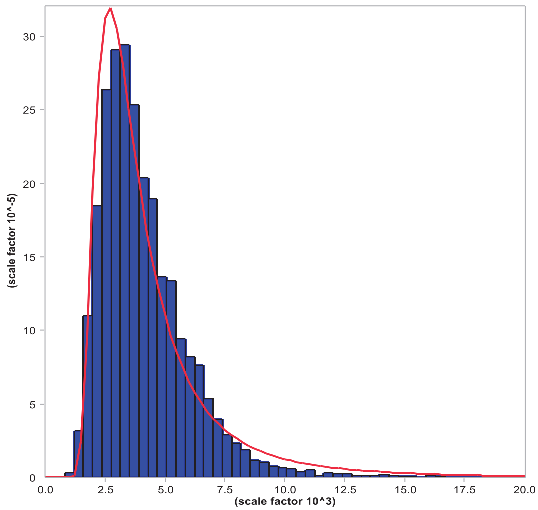

Figure E.1: Dagum distribution derived by maximum likelihood estimation as best fit on the data of the price per carat of finished stones.

Sensitivity analysis of polishing with an automatic DPS as a function of the final value per carat

This section presents the sensitivity analysis of the additional value of an automatic DPS as a function of the *final value per carat* of the stone. This final value determines the transport and capital savings, because both are driven by the value of the shipment. In Figures E.2 and E.3 a scatter plot is shown of the additional value of a DPS (on the Y-axis, which is left intentionally without scale) as a function of the final value per carat of the stone. Each point represents one simulation run (i.e. one stone) and is color-coded according to its weight category. The linear, upward evolution of the additional value (cfr. the trendlines in Figures E.2 and E.3) can be attributed to the increase in capital and transport savings for more valuable stones.

Analysis of the additional value of an automatic DPS through reduction of the probability of damage

A separate analysis was performed to estimate WTP_{PD}^{max}, the maximum value that can be added by reducing the probability of damaging the stone during polishing. For segments C and D, a scatter plot of the percentage of the cost

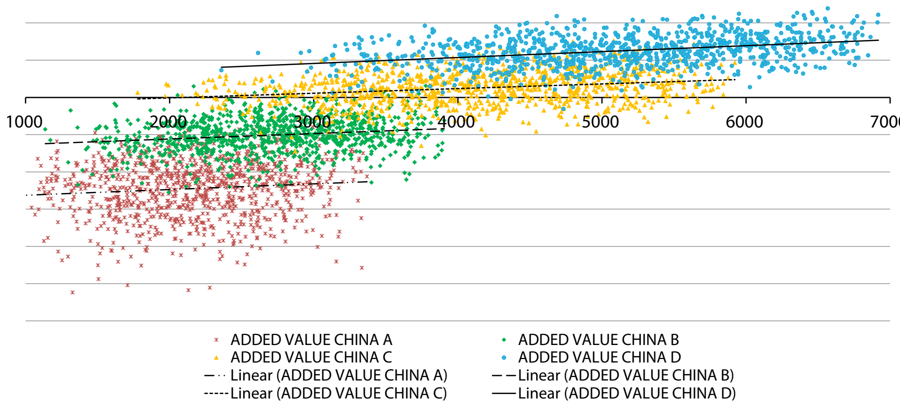

Figure E.2: Scatter plot (4000 simulations) of the additional value [US$] of an automatic DPS per carat versus polishing in China, as a function of the final value per carat of the diamond [US$]. Data points of the four weight categories are rendered in different colors.

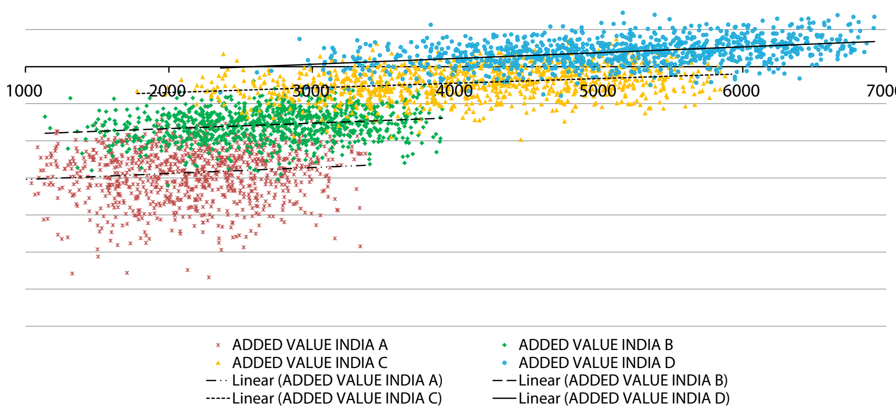

Figure E.3: Scatter plot (4000 simulations) of the additional value [US$] of an automatic DPS per carat versus polishing in India, as a function of the final value per carat of the diamond [US$]. Data points of the four weight categories are rendered in different colors.

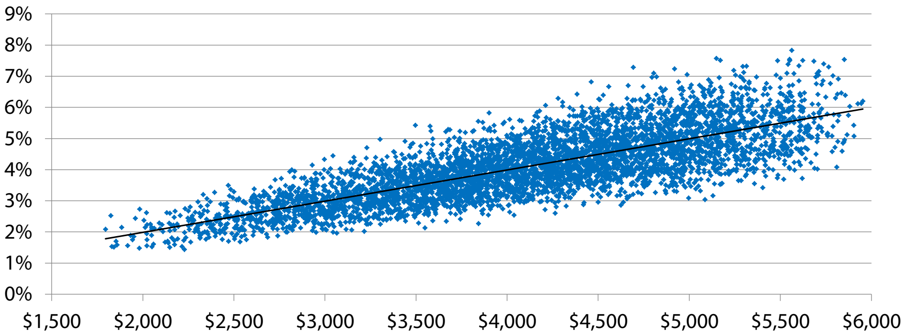

Figure E.4: Scatter plot (1000 iterations) of the maximum additional value that can be realized by reducing the probability of damaging a tension stone (segment C) during polishing, expressed as a percentage of the polishing cost per carat, as a function of the final value of the stone per carat.

Figure E.5: Scatter plot (1000 iterations) of the maximum additional value that can be realized by reducing the probability of damaging a tension stone (segment D) during polishing, expressed as a percentage of the polishing cost per carat, as a function of the final value of the stone per carat.

of polishing with the DPS that can be reduced for tension stones is depicted in Figures E.4 and E.5. In these figures, the assumption is made that we are dealing with a tension stone that belongs to one of four tension categories (cfr. Table E.3). Only in the last two categories damage can occur, the probability of which was estimated by an external expert.

From Figures E.4 and E.5 the conclusion can be drawn that the maximum additional value through reduction of the probability of damaging the stone is yet another term in Equation 8.2 that depends on the final value of the stone. Naturally, the more valuable the stone is, the graver the consequences of damage are. Depending on the final value per carat, for a C or D tension stone, on average maximally 2 to 6% or 2 to 8% of the polishing cost can be saved respectively, assuming that the probability of damage is reduced to zero. Hereby the assumption is made that in the outsourcing scenario, the financial consequences of damage are borne by the diamond processing company, not by the polishing subcontractor in China or India.

Conditions for a significantly large value for segment C

In Table E.4, the main conditions are stated such that the additional value of polishing with an automatic DPS is *on average* higher than 10% versus China. If one of these conditions is met, the average value passes this treshold. However, there is no guarantee that the additional value will *always* be higher than 10%.

Table E.4: Conditions such that the additional value (versus China) of polishing with an automatic DPS is on average higher than 10% of the polishing cost.

input parameter	**condition**
cost for polishing in China	$>$ 52.5 US$/ct rough
final weight of stone	$>$ 0.58 ct
final value of stone per carat	$>$ 4080 US$/ct
cost of polishing disk	$<$ 1200 US$/disk
lifetime of polishing disk	$>$ 30 stones

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Curriculum vitae

Joris Van Ostaeyen was born in Duffel (Belgium) on January 12, 1980. He holds a master's degree in electromechnical engineering from KU Leuven. After graduating in 2003, he joined Atlas Copco, a world-leading provider of sustainable productivity solutions, where he worked subsequently as quality, methods and process engineer in the Portable Air and Airtec divisions in Antwerp. From 2006 through 2007 Joris gained international experience in China, where he supported the implementation of Atlas Copco's new manufacturing plant of compressor elements in Wuxi, Jiangsu province. Before returning to Belgium, he took a sabbatical and traveled with his wife Barbara through South-East Asia, Latin America, the former Soviet Union and India.

Joris Van Ostaeyen joined the Centre for Industrial Management, Department of Mechanical Engineering, KU Leuven in 2009. His research interests include cost analysis, business model innovation and service development. From 2010-2013 his research work was supported by IWT under the collective research project Business Opportunities in Service Systems (BOSS), in collaboration with Sirris. In this project, Joris worked together with several Belgian manufacturers of investment goods to apply academic knowledge in an industrial context.

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